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Influence of plant density and varieties of different seed size on yield components and yield of Faba bean on *Vertisols* of Ethiopia

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Abstract: **Faba bean is a leading pulse crop grown in the central highland Vertisols of Ethiopia. However, waterlogging and lack of location-specific plant density recommendations constrained its productivity. Therefore, a field experiment was conducted during 2016 and 2017 to determine the effects of varieties of different seed size and plant density on yield and yield components of faba bean on Vertisols at Moretinajiru and Siyadebrinawayu districts. Factorial combinations of two varieties of faba bean ('Hachalu'- large-seeded and 'Lallo'-small-seeded) and five plant densities/seed rates (20, 40, 60, 80, and 100 plants m^{-2}) were tested in RCBD. Plant densities were converted to a seed rate of 144.7, 289.4, 434.1, 578.8 and 723.5 kg ha^{-1}, respectively, for variety 'Hachalu' while to a seed rate of 73.4, 146.8, 220.1, 293.5 and 366.9 kg ha^{-1}, respectively, for variety 'Lallo'. Plant density/seed rate showed a significant ($p<0.05$) effects on most of the studied parameters while variety and variety by plant density interaction showed a significant ($p<0.05$) effects only on some parameters considered. Grain yield of both varieties showed a quadratic response to increasing plant densities. Varieties 'Hachalu' and 'Lallo' with the respective plant density of 40 and 60 plants m^{-2} gave the corresponding highest net benefit of 26944.66 Ethiopian Birr ha^{-1} with a marginal rate of return of 120.87 %, and 31332.69 Ethiopian Birr ha^{-1} with marginal rate of return of 131.96 %.**

Keywords: **Broad-bed and furrow, Broadcast, economically optimum, Hachalu, Lallo, Waterlogging.**

1. INTRODUCTION

Faba bean (*Vicia faba* L.) is a leading crop in North Shewa and in Ethiopia among pulse crops in terms of area coverage and productivity. It covered 34.42 % (39,097.09 ha) of the land area of pulses in North Shewa Administrative Zone of Amhara Region, 23.30 % (162,003.90 ha) in Amhara region and 6.86 % (443,966.09 ha) of the land area of pulses in the country [8]. Its average yield is estimated to be 2.18 t ha^{-1} in the Zone, 1.75 t ha^{-1} in the Amhara region and 1.91 t ha^{-1} in the country [8] as compared to 1.7 t ha^{-1} of the world average [2]. The zonal average of this crop is still lower than the potential productivity of improved varieties released and recommended for similar areas [23]. This is due to several biotic and abiotic factors among which waterlogging is one of the major yield-reducing factors of the study area [22] and [15].

It is also known that plant density is one of several agronomic practices that affect the yield potential of faba bean [3]. Malek *et al*. (2012) as cited in Mondal *et al*. [25] stated that optimum plant density ensures proper growth of the aerial and underground parts of the plant through efficient utilization of solar radiation, nutrients, land as well as air spaces and water. On the other hand, the plant density of faba bean crop varied depending on the specific situation of each area (such as sowing time and seasonal moisture) and on the seed size. López-Bellido *et al*. [21] also indicated the presence of variations in optimum plant density depending on the botanical type (*major*, *equina* or *minor*) and the growth habit (determinate versus indeterminate) of faba bean cultivars tested. It is also to be noted that the plant population or seed rate is influenced by row width, crop species, soil, and climatic variables and crop use. In general, both genetic and environmental factors affect plant density [30]. According to Olson and Bowens [27], faba bean seed sizes range from 200 to 1000 gm per thousand seeds. Accordingly, in order to achieve optimum plant population several recommendations have been made within the country and around the globe for the production of faba bean cultivars on different soil types and management systems.

However, in Ethiopia, most of the recommendations were meant for a broadcast sowing of faba bean crop. For example, Amare and Adamu [4] recommended a seed rate of 175 and 200 kg ha^{-1} as a broadcast (which is estimated to be 35-40 plants m^{-2}), respectively, for mid and high altitude areas. They also noted that a seed rate of 250 kg ha^{-1} as broadcast on *Nitosols* and 350 kg ha^{-1} as drilling on camber bed on *Vertisols* resulted in the highest faba bean grain yield. Zewdu [36] also indicated that grain yield of faba bean significantly increased with increasing a seed rate from 170 to 260 kg ha^{-1} as a broadcast and presence of a significant variety by seed rate interaction around Sheno to Debre Birhan areas. Similarly, Adamu [1] reported that higher yields were obtained in most cases from higher seed rates of 260 to 370 kg ha^{-1} as a broadcast (which is estimated to be 52 to 74 plants m^{-2}) under BBF drainage system on pellic *Vertisols* of Sheno area. On the other hand, Mandefro *et al*. [22] recommended 40 cm row-to-row spacing and 5 cm plant-to-plant spacing for row sowing and 150 - 200 kg ha^{-1} for a broadcast sowing of faba bean crop. Getachew and Missa [15] also recommended a plant density of 40 - 50 plants m^{-2} depending on faba bean seed sizes, soil types and locations that did not cover higher altitudes such as Enewari.

Several recommendations have been made around the globe for row sowing of faba bean depending on seed size, management practices, and environmental factors. For example, Department of Environment and Primary Industries [10] recommended 20-30, 18-23 and 15 plants m^{-2} for the small, medium and larger seed size cultivars, respectively, by noting that lower rates apply to early sowing and the higher rates to late sowing for the State of Victoria. On the other hand, 40-45, 30-35 and 20 plants m^{-2} for the small, medium and larger seed size cultivars, respectively, have been recommended for Western Australian climate by the Department of Agriculture and Food [9]. Strydhorst and Olson [31] recommended 43 plants m^{-2} by indicating that plant density can be increased up to 65 plants m^{-2} as a risk management tool as higher plant density can hasten maturity on late sown faba bean crop and increase yields under dry conditions. Similarly, in the drier parts of the world like New Zealand about 96-130 plants m^{-2} [26] and in Jordan about 100 plants m^{-2} produced highest grain yields under irrigated conditions [34]. On the other hand, previous works in Europe recommended 20-25 plants m^{-2} for most soils and 15-20 plants m^{-2} for soils of high fertility where greater tillering is likely (Hebbelthwaite *et al*., 1983; cited in [15].

Traditionally farmers use handmade broad bed and furrow (HBBF – locally known as '*zekosh*') to solve the waterlogging problem. Studies also indicated that the integration of proper drainage with waterlogging tolerant and/or resistant varieties could tremendously improve the productivity of faba bean [13]. However, unlike flatbed practice under drained soil conditions, the production of faba bean under broad bed and furrow (BBF) production system forces farmers to leave one-third of the land uncultivated for drainage purposes. In addition to this, some of the seeds may be buried deep into the soil while covering. Similarly, some of the seeds could be exposed/uncovered and eaten by birds. Meanwhile, farmers of Enewari areas are being advised to use a seed rate of 135 – 140 kg ha^{-1} as a broadcast for the production of small-seeded faba bean varieties on the BBF production system. However, in practice, farmers use higher seed rates than the recommended rate (greater than 200 kg ha^{-1}). Studies on the yield and yield components response of faba bean varieties with different seed size and plant densities are very meager, if any, on Vertisols. Hence, this study was initiated to address the following objectives:

- ✓ To investigate the effects of varieties of different seed size and plant density on grain yield and yield components of faba bean;
- ✓ To determine seed size based plant density that maximizes economic productivity of faba bean on highland *Vertisols;*

2. MATERIALS AND METHODS

2.1 Description of the experimental site

The experiment was conducted at Burtilik (Moretinajiru district) and Ejersaqubeti (Siyadebrinawayu district) during the main rainy seasons of 2016 and 2017 from July to December on heavy *Vertisols*. The experimental sites are located at the latitude of 9^{0}53′ N and 9^{0}48′ N, the longitude of 39^{0}10′ E and 39^{0}12′ E and an altitude of 2665 and 2642 meters above sea level at Burtilik and Ejersaqubeti, respectively [19] and on-site record at Ejersaqubeti). The soil analysis results of the study sites revealed that the surface soil was clayey in texture. The amount of P found in the soil was below the requirement of faba bean (over 20 ppm), which is supposed to be supplemented using chemical fertilizers [16] (Table 1).

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Table 1: Pre-planting soil analysis results of the study site (for general information)

Parameter		Value		Rating/soil reaction class		Source of rating
		Average of environment one and three	Environment two	Average of environment one and three	Environment two	
Soil texture (%)	Clay	66	80			Hazelton and Murphy [18]
	Sand	6	10			
	Silt	28	10			
Texture class				clay	Clay	
pH		6.5	6.55	Slightly acidic	Slightly acidic	Tekalign [33]
Organic carbon (%)		1.2	1.07	low	Low	Tekalign [33]
Total nitrogen (%)		0.088	Nd	low	Nd	Tekalign [33]
Available phosphorus (ppm)		13.27	12.88	medium	medium	Cottenie [7]
Exchangeable K [cmol(+)/ kg soil]		0.73	0.63	high	High	FAO [12]
CEC [cmol(+)/ kg soil]		44	29.5	very high	High	Metson [24]

OC = organic carbon; TN = total nitrogen; Av.P=available phosphorus; CEC = cat-ion exchange capacity, SE=standard error of mean, nd=not determined, Environments one and three represent experiments done in 2016 and 2017 at Burtilik site while environment three represent experiment done on farmer field at Deneba in 2016

Source: *Debre Brehan agricultural research center (2015-2016)*

According to the unpublished data of the National Metrological Agency, the total rainfall for the period of July to August 2016 was higher than both the year 2017 and ten years average for the same period (Fig. 1). Generally, the total rainfall received for the months of July to December had a decreasing trend for the year 2016 while lacks trend for the year 2017 and for ten years average. The mean maximum temperature lacks trend for both years and ten years average (Fig. 1), hence difficult to indicate its impact. On the other hand, the mean minimum temperature showed a decreasing trend from July to December for the year 2016 and for ten years average while lacks trend for the year 2017 (Fig. 1).

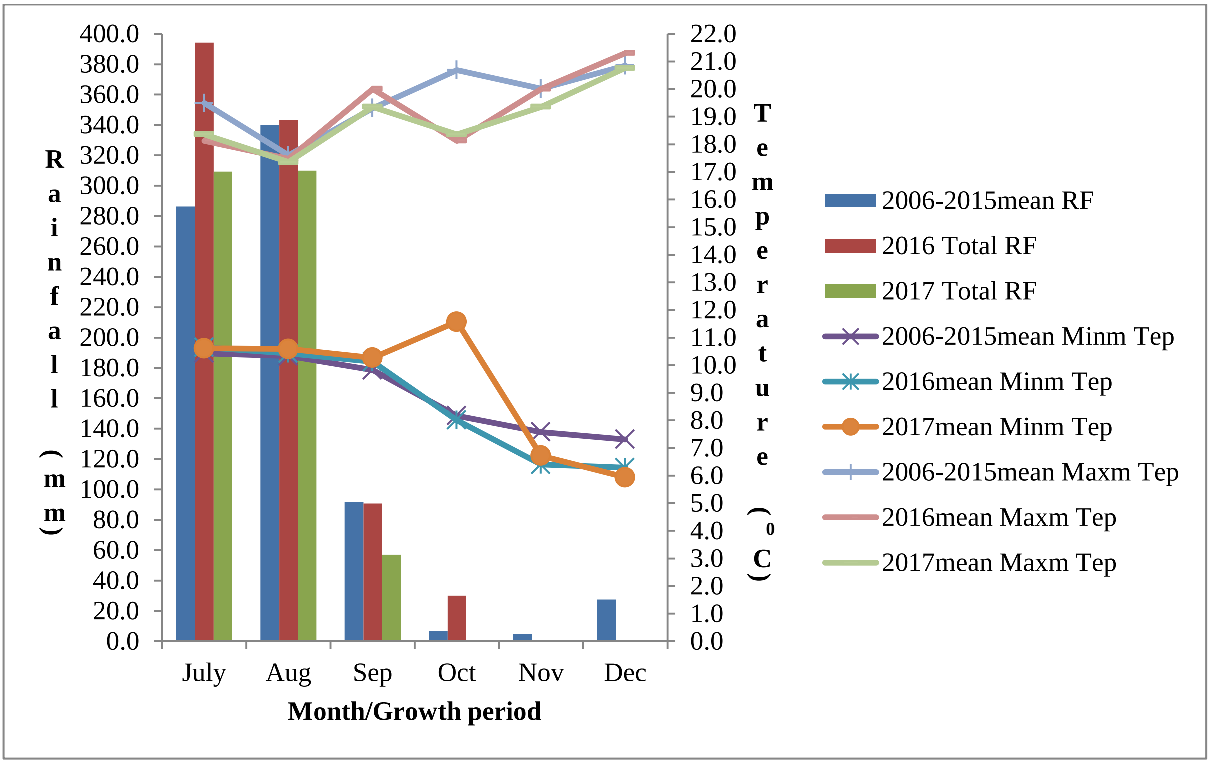

Figure 1: Rainfall (mm) and minimum and maximum temperatures for growth period of faba bean at Moretinajiru district

2.2 Treatments, experimental design, and procedures

The treatments consisted of complete factorial combinations of two improved varieties of faba bean ('Hachalu'- large-seeded and 'Lallo'- small-seeded) and five plant densities (20, 40, 60, 80, and 100 plants m^{-2}) laid out in randomized complete block design (RCBD), replicated four times at each site. Broadcast seed rates were prepared based on the plant density required per square meter. To calculate the seed rates, 100 seeds weight, germination rates, and 10 % field loss were used as estimation inputs for each variety separately. Accordingly, for variety 'Hachalu' the seed rates were 144.7, 289.4, 434.1, 578.8 and 723.5 kg ha^{-1} for 20, 40, 60, 80, and 100 plants m^{-2}, respectively, while for variety 'Lallo' the seed rates were 73.4, 146.8, 220.1, 293.5 and 366.9 kg ha^{-1} for 20, 40, 60, 80, and 100 plants m^{-2}, respectively. A gross plot size of 16.8 m^{-2} (4.8 m wide and 3.5 m long) on four broad beds and a net plot size of 8.4 m^{-2} (2.4 m wide and 3.5 m long) on the two central beds were used for data collection/measurement. Handmade broad bed and furrows drainage system, in which 80 cm wide bed and 40 cm wide-furrow with the depth of approximately 15 cm were opened for each bed. The seeds, based on each treatment level were uniformly broadcasted on each experimental plot before making furrows. Blanket recommendation of 100 kg NPS ha^{-1} chemical fertilizer was applied to each plot at sowing. Sowing was done on the 15th and 11th of July in the year 2016 and 2017, respectively, while harvesting was undertaken from the last week of October to mid of December in both years. Harvesting was done by cutting close to the soil surface using sickles. Two times hand weeding was done to control weeds. Root rot disease incidence affected less tolerant variety, 'Hachalu' during the early growth stage until flowering. However, it has been recovered in the later stages though some plants died. Root rot disease score was made using a 1- 9 rating scale during the late podding stage. Ball worm and gall disease were controlled by applying pesticides uniformly to each plot.

2.3 Crop data collection, measurement, and analysis

Data on plant height, number of primary branches $plant^{-1}$, number of pods $plant^{-1}$ and number of seeds pod^{-1} was measured from 10 randomly selected plants from central beds of each plot. Plant height was measured in cm from the ground to the tip of the main/mother stem at 90 % physiological maturity while the number of primary branches $plant^{-1}$, number of pods $plant^{-1}$ and number of seeds pod^{-1} were measured/counted at the time of harvest from 10 randomly selected plants. Days to flowering was recorded when 50% of the plants in a plot produced their first flower while days to physiological maturity was recorded when 90% of the plants in a plot reached physiological maturity. Grain yield was collected from central beds of each plot while 100 seeds weight was measured in grams of randomly counted 100 seed samples from each net plot. The straw yield was obtained by deducting grain yield from the total sundried above-ground biomass.

Data collected were subjected to the analysis of variance (ANOVA) following the statistical procedures stated by Gomez and Gomez [16] for two factors factorial experiments using SAS Software version 9.0 [29]. The mean comparison was performed using Duncan's Multiple Range Test (DMRT) at a 5% level of significance upon obtaining significant F-values of the factors and interactions. Two years data (two sites in 2016 and one site in 2017) were combined upon obtaining variance homogeneity, which was tested by employing Bartlett's test; otherwise, transformations were made using log and square root transformation techniques. Regression of grain yield of faba bean varieties of different seed sizes with plant densities was analyzed to see the relationship of yield and plant densities and to fit the response curve. The curve fit was done by employing a stepwise selection technique (using polynomial terms) for grain yield while power function for straw yield as it was the best fit by this technique. The socio-economic analysis was performed to assess farmers' evaluations in order to select the best treatment setup using farmers' evaluation criteria. The qualitative techniques were used to evaluate farmers' preferences. Around twenty-four (four female) farmers were invited to asses and select their best plant densities for each variety during the early physiological maturity of the crop. Concerning the merits of the varieties, 'Hachalu' variety is large seeded which had good adaptation to the *Vertisols* areas and high market preference while 'Lallo' is a small-seeded and well adapted to waterlogging conditions and more tolerant to root rot disease. The participants first visited all the seed rate levels of each variety independently and then discussed together to identify the most important selection criteria/attributes. Accordingly, they agreed on the Seed size, Number of pods per plant, Plant height, Number of seeds per pod and Number of primary branches per plant to be set as a common selection criterion. Pairwise and direct ranking matrix was performed to identify farmers' best choices (Tables not shown).

The economic analysis was performed on mean predicted values of grain- and straw yield (derived from the fitted regression equation) following the partial budget analysis method of CIMMYT [6]. The field price was obtained by a simple assessment of farm gate prices near the experimental field immediately after harvest (October - February) which was taken as the average of the two years. Accordingly, the prices of grain yield of 'Hachalu' and 'Lallo' faba bean varieties were found to be Ethiopian Birr (ETB) 15.50 and 13.00 kg^{-1}, respectively, while the price of the straw yield of both varieties was estimated as ETB 1.50 kg^{-1}. The variable costs included the cost of seed during sowing (June) and estimated as ETB 19.50 and 15.50 kg^{-1} for 'Hachalu' and 'Lallo', respectively. The opportunity cost of 5 % was considered for six months to allow for investing the additional money required for the extra seed. The cost of NPS fertilizer was not considered because it was applied uniformly to all plots. Cost of labor for weeding, harvesting, threshing, winnowing, packing and transporting per treatment was not considered because of difficulty in estimating as the experiment was done on a small plot [6] and, moreover, the differences were assumed negligible. The average yield was adjusted downward to 10 % assuming yield reduction by 10 % if farmers manage the same on a larger plot. In order to use the marginal rate of return (MRR) as a basis for variety and plant density recommendation, the minimum acceptable rate of return was set at 100 % [6]. Treatment with higher costs that vary and lower net benefit than the preceding treatment was considered to be dominated and was eliminated from further economic analysis.

3. RESULTS AND DISCUSSION

According to the combined analysis of variance over environments (two sites in 2016 and one site in 2017), environment by variety interaction showed a highly significant effect on most parameters studied while some of the interaction effects including variety by plant density were statistically significant (p< 0.05) on some parameters indicated in Table 2. On the other hand, the main effects of the environment and plant density were highly significant (p<0.01) on most yield and yield component parameters considered (Table 2).

Table 2: Mean squares of ANOVA for grain yield and some agronomic parameters of faba bean as affected by varieties of different seed size and plant density at Moretinajiru and Siyadebrinawayu districts, combined over environments (2 locations in 2016 and 1 location in 2017)

Source	DTF	DTM	Plh	NPB (Sqrt)	NPPP	NSPP	BRR (%) log	HSW	GY	SY
Environment (E)	28.16**	257.57**	169.76ns	0.643*	218.06**	0.91**	0.29**	479.02**	1.06ns	4.623**
E*Rep (R)	0.439	18.983	95.245	0.089	17.744	0.059	0.022	11.044	0.321	0.3250
Variety (V)	333.33ns	1178.13ns	1.78ns	0.020ns	51.09ns	0.37ns	1.15**	30729.60**	2.10ns	0.427ns
Plant density (P)	4.45*	177.51**	286.40**	0.027ns	247.83**	0.07ns	0.035ns	4.77ns	2.71**	2.324*
E*V	77.11**	174.51**	858.13**	0.0004ns	180.48**	0.15*	0.401**	34.51*	1.86**	3.250**
E*P	0.92ns	13.01ns	72.19ns	0.027ns	7.56ns	0.07ns	0.013ns	17.30ns	0.29ns	1.087**
V*P	0.37ns	24.53ns	40.31ns	0.027ns	53.44**	0.02ns	0.028ns	36.25*	0.13ns	0.345ns
E*V*P	1.06ns	9.65ns	41.77ns	0.019ns	10.52ns	0.03ns	0.018ns	16.16ns	0.06ns	0.050ns
Error	0.599	16.372	54.743	0.015	9.853	0.040	0.019	11.048	0.260	0.305

F test for the environment was performed by using E*R as a denominator while F test for main effects of variety and plant density were performed by using significant E*V and E*P interaction as a denominator; otherwise, the pooled error mean square was used as a denominator.

DTF=Days to 50% flower, DTM=Days to 90% physiological maturity, Plh=Plant height, NPB=Number of primary branches, NPPP=Number of pods per plant, NSPP=Number of seeds per pod, BRR=Black root rot score, HSW=Hundred seeds weight, GY=Grain yield, SY=Straw yield

3.1 Phenological and growth parameters

Though there was no significant difference between the varieties (seed size), early flowering (50.9 days) was recorded for variety 'Hachalu' while late flowering (54.2 days) was recorded for the variety 'Lallo' (Table 3). At all the three environments, variety 'Lallo' flowered later than variety 'Hachalu' (in the range of 0.3 days at environment three to 5.8 days at environment one) (Table 4). Environment one and three represent testing sites of Debre Birhan agricultural research center at Moretinajiru district where this experiment was conducted for two consecutive years (2016 and 2017) where as environment two represents a farmer's field where this experiment was conducted at Siyadebrinawayu district in 2016. The probable reason for the high numerical difference between environment one and three could be year variation that brought about lower rainfall, higher maximum and minimum temperature scores in 2017 that forced earlier flowering due to stress (Fig. 1, Table 4). On the other hand, in opposition to the results obtained for days to flowering, early maturity (136 days) was recorded for variety 'Lallo' while late maturity (142.2) was recorded for variety 'Hachalu', though there was no significant difference (Table 3). Variety 'Hachalu' matured later than variety 'Lallo' at all environments though the difference was insignificant at environment two (Table 4). This was probably related to recovery of large-seeded variety 'Hachalu' from root rot incidence and production of secondary growth which takes more time to mature while susceptibility of small-seeded variety 'Lallo' to desiccating wind that occurred due to higher maximum temperature at later growth stage which in turn leads to slightly forced maturity (Fig. 1).

Variation in plant densities significantly affected both days to flowering and maturity. Accordingly, days to flowering and maturity were reduced as plant density increased probably due to increased stresses for resource competition, which enhanced early flowering, and maturity at higher plant densities (Table 3). This result was in agreement with Khalil *et al.* [20] who reported that maximum days to flowering (54.2) were observed on plant density of 150,000 plants ha^{-1}, while minimum days to flowering (52.5 days) were on 600,000 plants ha^{-1} of faba bean. Similarly, Lopez-Bellido *et al.* [21] noted that high densities enhance the maturity of the crop.

A significant difference was not observed for plant height and the number of primary branches among the varieties tested. However, the two varieties responded differently at all environments for plant height. Though meteorology data is not available for Siyadebrinawayu district, variety 'Hachalu' had taller height at environment two while variety 'Lallo' had taller height at the rest environments (Table 4). Opposite to this result, Yucel [35] and Bakry *et al.* [5] reported significant differences among genotypes in terms of plant height and number of primary branches of faba bean under the Mediterranean type conditions of Turkey and under newly reclaimed sandy soil condition in Egypt, respectively. Though the highest number of primary branches was obtained from the lowest plant density, it was not significantly different from the rest levels while plant height on plant density of 80 plants m^{-2} increased by 10.9 % over that of 20 plants m^{-2} (Table 3). The probable reason for the increase in plant height could be the increase in the number of plants per unit area that resulted in high plant-to-plant competition for light. This result was in accordance with Yucel [35]; Bakry *et al.* [5]; and Getachew and Missa [15] who reported that the denser plant population increased the plant height due to competition among plants for light.

Table 3: Main effects of varieties of different seed size and plant density on grain yield (kg ha^{-1}) and some agronomic parameters of faba bean at Moretinajiru and Siyadebrinawayu districts, combined over environments (2 locations in 2016 and 1 location in 2017)

Treatment	SCH (m^{-2})	DTF	DTM	Plh (cm)	NPB(Sqrt)	NSPP	BRR(%)log	GY (t/ha)	SY (t/ha)
				Variety (seed size)					
Hachalu	59	50.9	142.2	74.0	0.78 (0.32)	2.2	15.71a (0.48)	2.25	1.95
Lallo	59	54.2	136.0	74.3	0.69 (0.29)	2.3	4.27b (0.29)	2.52	2.07
				Plant density (m^{-2})					
20 (109.1 kg ha^{-1})	21	53.1a	143.8a	69.9c	0.88 (0.36)	2.1	5.52 (0.36)	1.83c	1.54c
40 (218.1 kg ha^{-1})	42	52.9a	138.6b	71.2bc	0.67 (0.28)	2.3	10.45 (0.39)	2.31b	1.86b
60 (327.1 kg ha^{-1})	62	52.4b	138.7b	75.2ab	0.73 (0.30)	2.2	8.66 (0.36)	2.66a	2.14ab
80 (436.2 kg ha^{-1})	79	52.1b	137.2b	77.5a	0.61 (0.25)	2.2	11.16 (0.36)	2.60ab	2.30a
100 (545.2 kg ha^{-1})	92	52.3b	137.2b	77.1a	0.79 (0.32)	2.2	14.17 (0.45)	2.52ab	2.22a
Mean		52.6	139.1	74.2	0.74 (0.30)	2.2	0.38	2.38	2.01
CV (%)		1.47	2.91	9.97	9.50	9.06	35.65	21.39	27.44

SCH=Stand count at harvest, DTF=Days to 50% flower, DTM=Days to 90% physiological maturity, Plh=Plant height, NPB=Number of primary branches, NSPP=Number of seeds per pod, BRR=Black root rot score, GY=Grain yield, SY=Straw yield

Table 4: Two-way interaction effect of environment and varieties of different seed size on grain yield and some agronomic parameters of faba bean at Moretinajiru and Siyadebrinawayu districts, combined over environments (2 locations in 2016 and 1 location in 2017)

	Days to flower			Number of pods per plant			Grain yield (t ha^{-1})		
Variety (seed size)	Env. one	Env. two	Env. three	Env. one	Env. two	Env. three	Env. one	Env. two	Env. three
Hachalu (large seed size)	49.0d	50.4c	53.4b	10.8d	15.7b	16.5b	2.35bc	2.38bc	2.03c
Lallo (small seed size)	54.8a	54.3a	53.7b	14.8bc	19.2a	12.9c	2.79a	2.15c	2.62ab
Difference	-5.8	-3.9	-0.3	-4.0	-3.5	+3.6	-0.44	+0.23	-0.59
	mean=52.6, cv=1.5%			mean=15.0, cv=21.5%			mean=2.39, cv=21.6%		
	Days to mature			**Number of seeds per pod**			**Straw yield (t ha^{-1})**		
Variety (seed size)	Env. one	Env. two	Env. three	Env. one	Env. two	Env. three	Env. one	Env. two	Env. three
Hachalu (large seed size)	140.8b	139.8bc	146.1a	2.1c	2.1c	2.3b	2.02b	2.08b	1.75b
Lallo (small seed size)	132.3d	138.3bc	137.2c	2.1c	2.2bc	2.5a	2.77a	1.72b	1.72b
Difference	8.5	1.5	8.9	0.0	-0.1	-0.2	-0.75	+0.36	+0.03
	mean=139.1, cv=2.9%			mean=2.2, cv=9.1%			mean=2.01, cv=27.7%		
	Plant height (cm)			**Hundred seeds weight (g)**			**Black root rot (%)log**		
Variety (seed size)	Env. one	Env. two	Env. three	Env. one	Env. two	Env. three	Env. one	Env. two	Env. three
Hachalu (large seed size)	72.0c	80.5a	69.6c	60.07c	68.75a	64.77b	1.03b	0.66c	1.41a
Lallo (small seed size)	78.8ab	70.1c	74.0bc	30.17e	35.33d	32.08e	0.32d	0.79c	0.69c
Difference	-6.8	+10.4	-4.4	29.9	33.42	32.69	0.71	-0.13	0.72
	mean=74.2, cv=10.4%			mean=48.53, cv=6.9%			mean=0.81, cv=33.6%		

Env.=Environment

3.2 Yield components and yield

The two varieties responded differently for the number of pods per plant and a hundred seeds weight at varying levels of plant density. Accordingly, for both varieties significantly the highest number of pods per plant (18.5 and 22.5 for 'Hachalu' and 'Lallo', respectively) was recorded under plant density of 20 plants m^{-2} (Table 5). On the other hand, number of pods per plant in 'Lallo' was higher than that of Hachalu by 5.4 (at plant density of 40 plants m^{-2}) and 4.0 (at plant density of 20 plants m^{-2}) while the difference was negligible at plant density of 60 and 80 plants m^{-2}; on the other hand, variety 'Hachalu' produced 2.7 number of pods per plant than Lallo at plant density of 100 plants m^{-2} (Table 5). Similarly, variety 'Hachalu' produced a higher number of pods per plant at environment three than the rest environments probably attributed to the amount and distribution of rainfall that favored late maturing variety 'Hachalu' more (especially in 2017 or environment three) (Table 4, Fig. 1). According to Lopez-Bellido *et al.* [21], despite considerable variation, number of pods per plant decreases with increasing density but is compensated by a larger number of plants per square meter, resulting in a larger number of pods per square meter and thus greater yields, although at very high plant densities this component shows no clear trend. Concerning a hundred seeds weight, for large-seeded variety 'Hachalu' the heaviest hundred seeds weight (65.78g), though not significantly different from other plant density levels were recorded under plant density of 60 plants m^{-2} (434.1 kg ha^{-1}). On the other hand, for variety 'Lallo' the heaviest hundred seeds weight (34.87 gm) was recorded under plant density of 20 plants m^{-2} (73.4 kg ha^{-1}). Hundred seeds weight in 'Hachalu' was higher than that of 'Lallo' by 28.06, 31.11, 33.78, 33.51 and 33.55 at a plant density of 20, 40, 60, 80 and 100 plants m^{-2}, respectively (Table 5). Similarly, variety 'Hachalu' produced heaviest hundred seeds weight than 'Lallo' in all environments (Table 4). As indicated in Yucel [35] hundred seeds weight of faba bean reflects the ability of the genotypes to partition its dry matter into seed where small seeds develop rapidly once the reproductive phase starts and produce less dry matter in their seed. Hence, due to the decrease of assimilates, small seeds produce less seed weight.

Table 5: Two-way interaction effect of varieties of different seed size and plant density on some agronomic parameters of faba bean at Moretinajiru and Siyadebrinawayu districts, combined over environments (2 locations in 2016 and 1 location in 2017)

Variety (seed size)	Plant density m^{-2}				
	20	40	60	80	100
	Number of pods per plant				
Hachalu (large seed size)	18.5b	12.9d	12.3d	13.0d	15.0cd
Lallo (small seed size)	22.5a	17.5bc	13.1d	12.9d	12.3d
Difference	-4.0	-5.4	-0.8	+0.1	+2.7
	Mean= 15.0, CV= 20.94				
	Hundred seeds weight (g)				
Hachalu (large seed size)	62.93a	64.04a	65.78a	64.56a	65.33a
Lallo (small seed size)	34.87bc	32.93bc	32.00c	31.05c	31.78c
Difference	28.06	31.11	33.78	33.51	33.55
	Mean= 48.53, CV= 6.85				

CV= Coefficient of variation, Means in column and row followed by the same letters are not significantly different at 5% level of significant

There was no significant difference between varieties for the number of seeds per pod. However, the highest number of seeds per pod (2.3) was recorded for small-seeded variety 'Lallo' while the lowest (2.1) was for large-seeded variety 'Hachalu' (Table 3). The difference across environments was negligible (Table 4) as the number of seeds determined more by genotype than the environment [21]. Concerning plant density, changing plant density had no significant effect on the number of seeds per pod, as it is mainly genotype dependent (Table 3). In agreement with this result, Lopez-Bellido *et al*. [21] and Getachew and Missa [15] reported that the number of seeds per pod was not significantly affected by changing the level of plant density of faba bean.

Though there was no significant difference between the varieties (seed size) tested, highest grain yield (2.52 t ha^{-1}) and straw yield (2.07 t ha^{-1}) was obtained for variety 'Lallo' while the lowest grain yield (2.25 t ha^{-1}) and straw yield (1.95 t ha^{-1}) was for variety 'Hachalu' (Table 3). Variety 'Hachalu' produced the highest grain- and straw yield at environment two though metrological data is not available for that locality (Table 4). As indicated in Table 6, grain yield showed a positive and highly significant association with plant height at all environments as well as averaged over three environments. Similarly, grain yield was positively and highly significantly correlated with the straw yield at environment one, two and averaged over three environments, but there was a non-significant positive association at environment three. On the other hand, there was a negative but significant association between grain yield and black root rot incidence in all environments as well as averaged over three environments. Other traits showed negative correlations with grain yield (except a few positive associations). This result reflected the importance of plant height, straw yield, and severity of black root rot incidence in the determination of grain yield at the study area. In agreement with this result, Tadele *et al.* [32] reported the presence of a positive association between grain yield and plant height at Sinan on *Vertisols*. Similarly, Salem [28] reported the presence of significant positive correlations between faba bean seed yield and biological yield.

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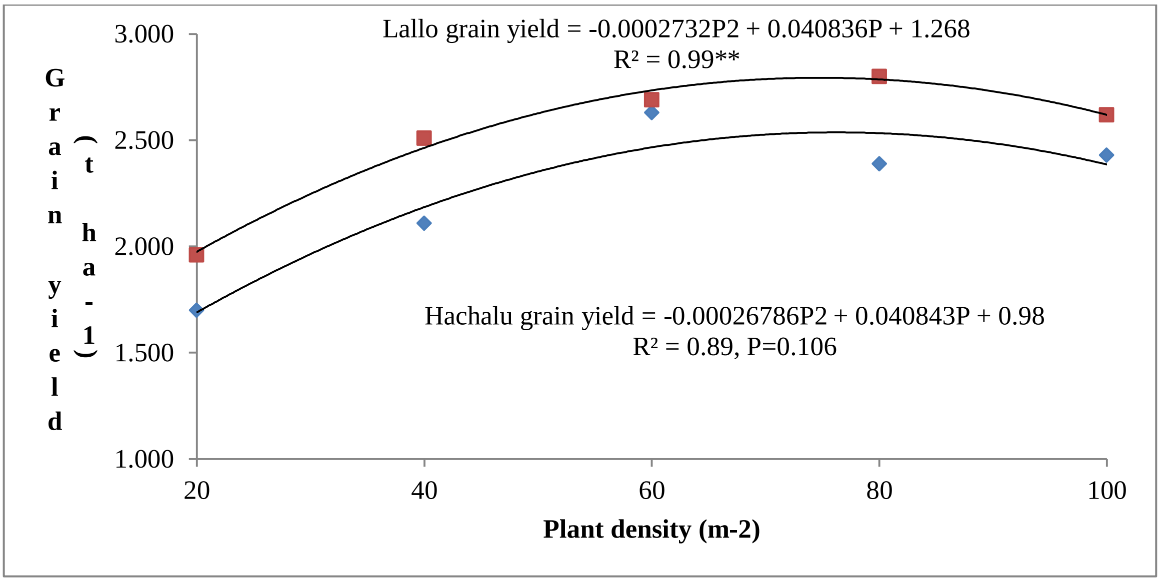
Table 6: Correlation coefficients between faba bean grain yield and other studied characters at three environments in Moretinajiru and Siyadebrinawayu districts

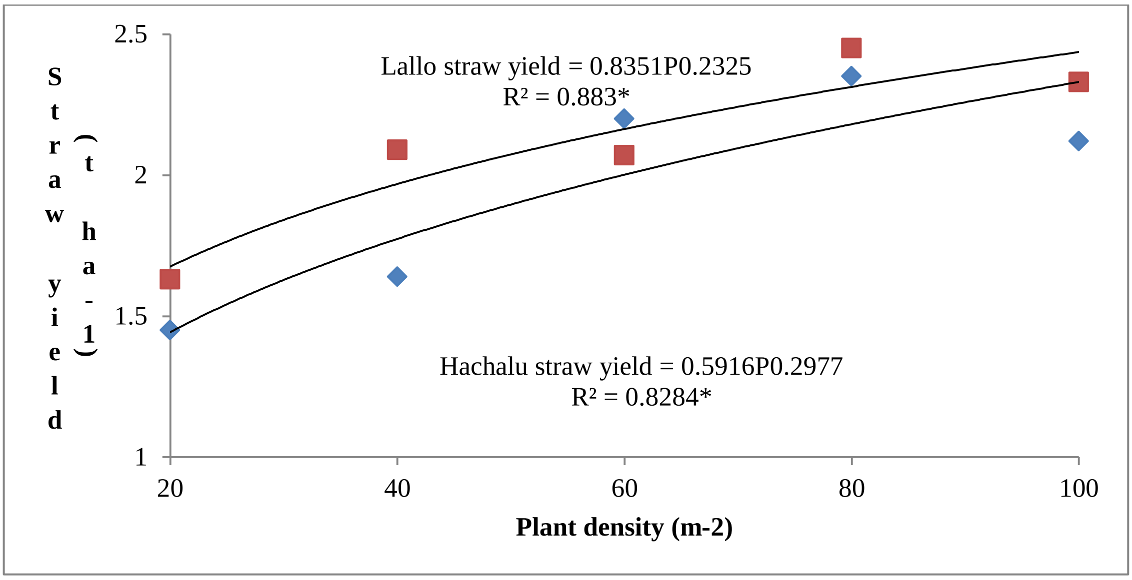
	Grain yield			
Yield components	Environment one	Environment two	Environment three	averaged over three environments
Days to flower	0.3454*	-0.4632**	-0.0988ns	-0.1097ns
Days to mature	-0.4760**	-0.7934**	-0.5242**	-0.50876**
Plant height	0.6103**	0.8090**	0.5392**	0.6583**
Number of pods per plant	0.0135ns	-0.5055**	-0.3252*	-0.2284*
Number of seeds per pod	-0.2279ns	0.1098ns	0.3413*	-0.1955*
Black root rot percent (log)	-0.5995**	-0.5033**	-0.4613**	-0.4611**
Hundred seeds weight	-0.3219*	0.2116ns	-0.5217**	-0.0829ns
Straw yield	0.8604**	0.8910**	0.3090ns	0.7497**

Concerning plant density, grain yield and straw yield showed a decreasing trend after plant density of 60 plants m^{-2}, that is why grain yield response to increasing plant density was significantly quadratic (Fig. 2). The highest grain yield (2.66 t ha^{-1}) and straw yield (2.30 t ha^{-1}) and the lowest grain yield (1.83 t ha^{-1}) and straw yields (1.54 t ha^{-1}) were obtained from plant density of 60 plants m^{-2} and 20 plants m^{-2}, respectively (Table 3). In support of this result, Getachew and Missa [15] made location-specific recommendations based on seed size for Nitosols and light Vertisols of Jeldu, Holetta and Adadi areas. The soil analysis report of these areas indicated that Holetta and Jeldu areas are found to be sub-optimal for faba bean production because of their low pH and low content of available P. Accordingly, these areas responded differently and a specific recommendation was made. Hence, for small seed size: 40 plants per square meter for Holetta in particular and 50 plants per square meter for Adadi and Jeldu areas; for medium seed size: 50 plants per square meter for Jeldu and Holetta areas, and 40 plants per square meter for Adadi area; and for large seed size: 50 plants per square meter for all the three test locations. Turk and Tawah [34] also reported that for faba bean cultivar '*minor*' seed yield increased with increasing plant density, the highest yield obtained being at 100 plants m^{-2}. In our study, grain yield of both varieties showed a quadratic response to increasing plant densities ranging from 20 to 100 plants m^{-2}; R^2 values for the curve fit being 0.89 and 0.99** for 'Hachalu' and 'Lallo', respectively (Figure 2). On the other hand, the relationship of straw yields of both varieties to increasing plant densities ranging from 20 to 100 plants m^{-2} explained more significantly by power function than polynomial terms, R^2 values for the curve fit being 0.83* and 0.88* for 'Hachalu' and 'Lallo', respectively (Figure 3).



P=Plant density

Fig. 2: Relationship between grain yields of faba bean varieties of different seed size and plant density



P=Plant density

Fig. 3: Relationship between straw yields of faba bean varieties of different seed size and plant density

3.3 Incidence of black root rot disease

Significantly ($p<0.05$) the highest black root rot incidence (15.71%) was recorded for large-seeded variety 'Hachalu' and the lowest (4.27 %) was recorded for small-seeded variety 'Lallo' (Table 3). However, variety 'Lallo' was affected more at environment two than 'Hachalu' though the difference was not significant (Table 4). According to their history from variety registration, variety 'Lallo' was more tolerant to root rot and more specifically recommended for heavy *Vertisols* areas whereas variety 'Hachalu' was meant for wider adaptation on *Vertisols*. Even though there was a large difference between the lowest and the highest plant densities effects on the incidence of black root rot, the statistical analysis failed to detect this difference. The highest black root rot incidence of 14.17 % was recorded on the highest plant density, 100 plants m^{-2}, while the lowest incidence of 5.52 % was recorded on the lowes plant density, 20 plants m^{-2} (Table 3). However, this may not indicate the relation between plant population and root rot incidence as it is a soil brone disease that had patchy and variable distribution in the field [11].

3.4 Socioeconomic analysis

3.4.1 Farmers' assessment

The evaluation was carried out by selecting the best replication (out of four replications) on which all the five plant densities of each variety performed well. During the evaluation, they considered the overall performance of plant densities of each variety separately. Accordingly, for variety 'Hachalu', they selected plant densities of 40, 60 and 20 plants m^{-2} as 1st, 2nd and 3rd choices, respectively. On the other hand, for variety 'Lallo', they selected plant densities of 20, 40 and 80 plants m^{-2} as 1st, 2nd, and 3rd choices, respectively.

3.4.2 Economic analysis

Separate economic analysis was performed for each variety on mean predicted grain and straw yields based on CIMMYT [6]. Accordingly, for large-seeded variety 'Hachalu', increasing plant density from 20 plants m^{-2} to 30 plants m^{-2} had a marginal rate of return of 175.33 %. Further increasing to 40 plants m^{-2} had marginal rate of return of 120.87 %; which is above the acceptable minimum rate of return of 100 % and suggests for each Ethiopian Birr (ETB) invested in faba bean production by using variety 'Hachalu' at planting density of 40 plants m^{-2}, the producer would get ETB 1.21 after recovering the investment cost (Table 7). For small-seeded variety 'Lallo', increasing plant density from 20 plants m^{-2} to 30 plants m^{-2} had a marginal rate of return of 469.114 %, which is higher than the acceptable minimum rate of return of 100 %. Further increase in plant density up to 60 plants m^{-2} also gave a higher marginal return than the acceptable minimum (Table 8). Hence, if the producer prefers to use a plant density of 60 plants m^{-2}, he/she would get ETB 1.32 after recovering the investment cost.

Our study revealed that variety Lallo exhibited a wider elastic yield response to planting densities as compared to that of variety Hachalu. According to Al-Suhaibani [3], the optimum plant density to obtain high productivity for different faba bean varieties can range from 10 to 100 plants m^{-2} indicating that the faba bean crop has the ability to alter plant size and canopy structure in response to changes in plant density. However, Graf and Rowland [17] noted that the marginal response in yield is very small at high densities for this crop. Therefore, when the marginal cost of an increase in plant density approaches, the marginal return from the increase in yield, further increases in seeding rate are not warranted.

Table 7: Dominance and marginal rate of return analysis for the effect of varieties of different seed size and plant density on grain- and straw yield (t ha^{-1}) of faba bean variety *'Hachalu'* at Moretinajiru and Siyadebrinawayu districts, combined over environments (2 locations in 2016 and 1 location in 2017)

Plant density (m^{-2})	Seed rate (kg ha^{-1})	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Adjusted grain yield (t ha^{-1})	Adjusted straw yield (t ha^{-1})	GB (sum of GY&SY) (Birr/ha)	TVC (Birr/ha) (sum of GY&SY)	NB (Birr/ha) (sum of GY&SY)	MRR (%) (sum of GY&SY)
20	144.70	1.69	1.44	1.52	1.30	25519.50	2962.80	22556.70	
30	217.10	1.96	1.63	1.77	1.47	29598.30	4444.20	25154.10	175.33
40	289.40	2.19	1.77	1.97	1.59	32870.25	5925.59	26944.66	120.87
50	361.80	2.35	1.90	2.12	1.71	35389.35	7406.99	27982.36	70.05
60	434.10	2.47	2.00	2.22	1.80	37100.70	8888.40	28212.30	42.79
70	506.50	2.53	2.10	2.27	1.89	38072.70	10369.79	27702.91	D
80	578.80	2.53	2.18	2.28	1.96	38278.35	11851.19	26427.16	D
90	651.20	2.49	2.26	2.24	2.03	37730.70	13332.60	24398.10	D
100	723.50	2.39	2.33	2.15	2.10	36430.20	14813.99	21616.21	D

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

Table 8: Dominance and marginal rate of return analysis for the effect of varieties of different seed size and plant density on grain- and straw yield (t ha^{-1}) of faba bean variety '*Lallo'* at Moretinajiru and Siyadebrinawayu districts, combined over environments (2 locations in 2016 and 1 location in 2017)

Plant density (m^{-2})	Seed rate (kg ha^{-1})	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Adjusted grain yield (t ha^{-1})	Adjusted straw yield (t ha^{-1})	GB (sum of GY&SY) (Birr/ha)	TVC (Birr/ha) (sum of GY&SY)	NB (Birr/ha) (sum of GY&SY)	MRR (%) (sum of GY&SY)
20	73.40	1.98	1.68	1.78	1.51	25375.50	1194.27	24181.23	
30	110.10	2.25	1.84	2.02	1.66	28773.90	1791.41	26982.50	469.11
40	146.80	2.46	1.97	2.22	1.77	31488.30	2388.54	29099.76	354.57
50	183.50	2.63	2.07	2.36	1.86	33530.40	2985.68	30544.73	241.98
60	220.10	2.74	2.16	2.46	1.94	34915.50	3582.81	31332.69	131.96
70	256.80	2.79	2.24	2.51	2.02	35643.60	4179.95	31463.66	21.93
80	293.50	2.79	2.31	2.51	2.08	35714.70	4777.08	30937.62	D
90	330.20	2.73	2.38	2.46	2.14	35154.00	5374.22	29779.79	D
100	366.90	2.62	2.44	2.36	2.20	33948.00	5971.35	27976.65	D

*Pred=Predicted, GB= Gross benefit, TVC= Total variable cost, NB= Net benefits, MRR= Marginal rate of return,*D= Dominated

4. CONCLUSION

This study indicated that the main effects of plant density showed a significant effect on grain yield and some of the yield components of faba bean varieties. Farmers' preference and economic analysis results matched for variety 'Hachalu' while there was a deviation for variety 'Lallo' probably due to farmers' preference (seed rate of 73.4 kg ha^{-1} or 20 plants m^{-2}) could not repeat its performance across replications. However, grain yield of both varieties showed a quadratic relationship to the changes in plant density levels. Depending on the agronomic and economic analysis results, it can be concluded that variety 'Hachalu at a seed rate of 289.4 kg ha^{-1} (40 plants m^{-2}) and variety 'Lallo' at a seed rate of 220.1 kg ha^{-1} (60 plants m^{-2}) found to be optimum for a broadcast sowing of faba bean. However, producers who have limited access to resources could use variety 'Hachalu' at a seed rate of 217.1 kg ha^{-1} (30 plants m^{-2}) as a second choice. Similarly, since variety 'Lallo' exhibited a wider elastic yield response, such producers could use it at a seed rate of 183.5 kg ha^{-1} (50 plants m^{-2}), 146.8 kg ha^{-1} (40 plants m^{-2}) and 110.1 kg ha^{-1} (30 plants m^{-2}) as second, third and fourth choices, respectively, for broadcast sowing of faba bean on highland *Vertisols* of Moretinajiru and Siyadebrinawayu districts.

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