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Faba bean is a leading pulse crop grown in the highland Vertisols *of North Shewa, although waterlogging and a lack of specific plant density recommendations based on seed size constrained its productivity in the broad bed and furrow soil drainage system. A field experiment was conducted to study the effects of seed size and plant density on yield and yield components of faba bean varieties on highland* Vertisols *at Enewarie in 2015 and 2016. Factorial combination of two varieties of faba bean* Hachalu *(large-seeded) and* Lallo *(small-seeded) and five plant densities (20, 40, 60, 80, and 100 plants* m^{-2}*) in row planting spaced at 40 cm was laid out in a randomized complete block design with four replications. Variety and plant density main effects showed significant (*$p<0.05$*) effects on most of the studied parameters, while variety by plant density interaction effects was significant (*$p<0.05$*) for physiological maturity, number of primary branches per plant, and grain yield. Although the two varieties have the same recommendable planting density of 40 plants* m^{-2} *in row planting, the net benefit and marginal rate of return are higher for variety* Hachalu *because of its larger seed size associated with a higher price in the local market. Therefore, a planting density of 40 plants* m^{-2} *in 40cm spaced rows is recommended for the production of the large-seeded faba bean variety* Hachalu *with a matching seed rate of about 298 kg* ha^{-1} *on relatively light* Vertisols*, and the small-seeded faba bean variety* Lallo *with a matching seed rate of about 139 kg* ha^{-1} *on heavy* Vertisols *in the highlands of North Shewa and similar areas. We have also observed that higher seed rates enhance emergence and maturity, which are important for further research to improve frost escape mechanisms in high-altitude areas where frost is a problem.*

ffi : Faba bean, large seed size, marginal rate of return, net benefit, seed rate, small seed size

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Faba bean (*Vicia faba* L.) is a leading crop among pulse crops in an area of production and productivity in the highlands of North Shewa in particular and in Ethiopia in general. It covers about 34.42% (39097.09 ha) land area of pulses in the North Shewa Zone and about 26.86% (443966.09 ha) land area of pulses in the country (CSA 2016). Its average yield is estimated to be 2.2 t ha^{-1} in the Zone and 1.9 t ha^{-1} in the country (CSA 2016). The zonal average is still lower than the potential productivity (on average 3.55 t ha^{-1}) of improved varieties released and/or recommended for production in the zone (MoA 2014). This is due to several biotic and abiotic factors, among which waterlogging is one of the major factors reducing the productivity of faba bean in the study area (Getachew and Missa 2011).

Traditionally farmers use handmade broad beds and furrows (HBBF – locally known as *zekosh*) to solve waterlogging problems. However, unlike the flatbed practice of undrained soil conditions, the production of pulse crops especially faba bean under broad bed and furrow (BBF) soil drainage system forces farmers to leave one-third of the land uncultivated for drainage purposes. Hence, this may require the recommendation of separate/specific plant density (seed rate) for BBF soil drainage system. In addition to this, no plant density (seed rate) has been recommended for row planting of faba been under BBF soil drainage system. It is also known that plant density is one of several agronomic practices that affect the yield potential of faba bean (Al-Suhaibani *et al* 2013). Malek *et al* (2012) as cited in Mondal *et al* (2014) 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 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* (2005) also indicated 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. 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. In general, both genetic and environmental factors affect plant density (Shirtliffe *et al* 2007). According to Olson and Bowens (2014), faba bean seed sizes range from 200 to 1000 g 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.

In Ethiopia, most of the recommendations were meant for the broadcast sowing of faba bean. For example, Amare and Adamu (1994) 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 350 kg ha^{-1} as drilling on a cambered bed on *Vertisols* resulted in the highest faba bean grain yield. Zewdu (1992) also indicated that the grain yield of faba bean significantly increased with increasing a seed rate from 170 to 260 kg ha^{-1} as a broadcast and noted a significant variety by seed rate interaction around Sheno to Debre Brehan areas. Similarly, Adamu (1996) reported higher yields 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* (2009) recommended 40 cm row-to-row spacing and 5cm plant-to-plant spacing for row sowing and 150-200 kg ha^{-1} for a broadcast sowing of faba bean crop regardless of soil type and drainage system. However, Getachew and Missa (2011) recommended plant density of 40-50 plants m^{-2} depending on faba bean seed sizes for Adadi light *Vertisols* although the medium and large seed size varieties which had been tested are not recommended to water-logging heavy *Vertisols* of high altitude areas such as Enewari in the highlands of North Shewa. Similarly, Almaz *et al* (2016) reported higher yields from a combination of 30 cm inter, and 8 cm intra-row spacing for Gachena large-seeded faba bean variety under Haramaya *Vertisols* for a flatbed production system. Kubure *et al* (2016) also reported higher yields from a combination of 30 cm inter, and 7.5 cm intra-row spacing for *Wolki* and *Hachalu* large-seeded faba bean varieties on *Pellic Vertisols* at Ambo for a flatbed production system. So far, studies on row planting of faba bean varieties with different seed sizes are very few, if any, BBF soil drainage systems. This may be associated with the difficulty of management of *Vertisols* because of its poor internal drainage and resultant flooding and waterlogging during the rainy season. Hence, preparing beds and making rows at the same time creates difficulty in a very muddy condition of this soil. On the other hand, though it is time-consuming and labor-intensive, row planting could be possible by using early planting of root rot tolerant varieties of faba bean. Therefore, this study was initiated to assess the effects of different seed sizes and row planting density of faba bean varieties on yield and yield components under BBF soil drainage system and determine seed size based on economically optimum row planting density that maximizes the productivity of faba bean varieties under BBF soil drainage system on *Vertisols.*

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The experiment was conducted at Enewarie in Moretinajiru district (Burtilik testing site) in 2015 and 2016 from July to December on heavy *Vertisols*. The geographic coordinate of the test location is $9^0$53′ N latitude, and $39^0$10′ E longitude with an altitude of 2665 meters above sea level.

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About one kg composite soil sample was collected from the whole plot (from five spots) in a zigzag pattern to the depth of 0-30 cm just before sowing for determining textural class, soil pH, organic matter, cation exchange capacity (CEC), total N, available P, and available K. Soil texture analysis was done by using hydrometer method as stated by Hazelton and Murphy (2007), soil pH was tested by using the potentiometric method described by Murphy (1968), organic matter was determined by using Walkley and Black method Tekalign (1991), CEC was determined by flame photometer described by Metson (1961), total N was determined by modified Kjeldahl method described by Tekalign (1991), available P was determined by using Olson's method described by Tekalign (1991), and available K was determined by flame photometer described by FAO (2006).

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Daily rainfall, maximum and minimum temperature data were recorded at Enewari metrology station by employees of the National Meteorology Agency. Secondary data were also collected from National Meteorology Agency, Kombolcha branch directorate (unpublished data) to see the long-term averages for comparison.

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The treatments included a complete factorial combination 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}). Accordingly, a 2 x 5 complete factorial arrangement was implemented in a randomized complete block design (RCBD) with four replications. Row-to-row distance of 40 cm was maintained constant for all treatments. The desired plant population was obtained by varying plant-to-plant distance for each plant density separately. Accordingly, 40 x 12.5, 40 x 6.25, 40 x 4.17, 40 x 3.13 and 40 cm x 2.5 cm spacing were used to get 20, 40, 60, 80 and 100 plants m^{-2}, respectively. On the other hand, seed rate was obtained by using the equation stated by Matthews (2005) as:

$$\text{Seed rate (kg ha}^{-1}\text{)} = \frac{\text{Target plant density (m}^{-2}\text{)} * \text{100 seed weight (g)} * 10}{\text{Germination percentage} * \text{Establishment percentage}}$$

Accordingly, t

picked 100 seed samples from grain yield harvest in each net plot. Harvest index was calculated as a ratio of grain yield to the aboveground dry biomass.

Data were subjected to the analysis of variance (ANOVA) following the statistical procedure for two-factor factorial experiments using SAS Software version 9.0 (SAS 2002). Mean comparison was performed using Duncan's Multiple Range Test (DMRT) at a 5% level of significance upon obtaining significant F-values of the main effects and interactions. Two years' data were combined upon obtaining variance homogeneity, which was tested by employing Bartlett's test. The F test for the year was performed by using replication by year interaction term as a denominator while the F test for other main effects was performed by using significant year by factor interaction as a denominator; otherwise, the pooled error mean square is used as a denominator (Petersen 1994). Stepwise regression at a 5% probability level was also done for each grain and straw yield response of faba bean varieties as affected by plant densities.

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 (1988). The field price was obtained by a simple assessment of farm gate prices near the experimental field after harvest (January to February), which was taken as an average of the two years. Accordingly, the prices of the grain yield of Hachalu and Lallo faba bean varieties were 14 and 11 Ethiopian Birr (ETB) kg^{-1}, respectively, while the straw price was 1.50 ETB kg^{-1} for both varieties. The variable costs included the cost of seed during sowing (June) and were estimated as 18.00 and 14.5 ETB kg^{-1} for Hachalu and Lallo varieties, respectively. The average yield was adjusted downward to 10%, assuming a yield reduction by 10% if farmers managed the same on a larger plot. In order to use the marginal rate of return (MRR) as a basis for variety and plant density recommendations, the minimum acceptable rate of return was set at 100% (CIMMYT 1988). A treatment having a higher total cost that varies and a lower net benefit than the immediate preceding treatment with a lower total cost that varies and a higher net benefit was considered to be dominated and was eliminated from further analysis.

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The soil analysis of the study site revealed that the surface soil of the experimental field was clay in texture, neutral in pH (6.60), low in organic carbon content (1.18%), low in total nitrogen content (0.09%), medium in available phosphorus (0.01 mg/g), high in exchangeable potassium [0.73 cmol(+) kg^{-1} soil] and very high in cation exchange capacity [49.13 cmol(+)/ kg soil].

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According to unpublished data of the National Metrological Agency (Figure 1), rainfall amount was lower for the year 2015 than the year 2016 and nine years' average (2006 to 2014). The maximum temperature was higher for the year 2015 than the year 2016 and nine years' average for most months although all showed inconsistent trends (Figure 1). On the other hand, mean minimum temperature showed a decreasing trend from July to December for all years. However, the highest mean minimum temperature was recorded for the year

2015 with the exception of September (Figure 1).

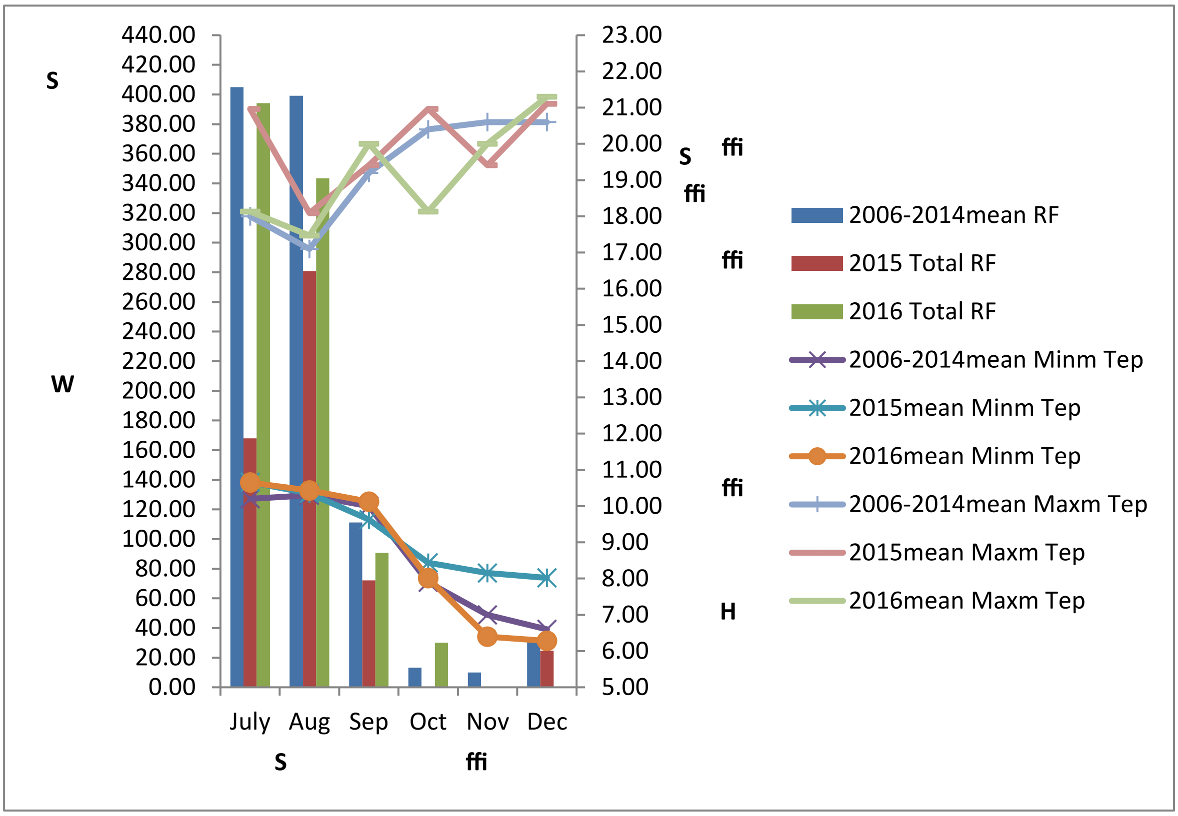

Figure 1. Nine years (2006 - 2014) average, the year 2015 and 2016 monthly rainfall, maximum and minimum temperatures of faba bean growing period at Enewarie

ffffi National Meteorology Agency, Kombolcha branch directorate (unpublished data)

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The results of the combined analysis of variance over years (2015 and 2016) of yield-related parameters, yield components, and yield of faba bean varieties as affected by plant density are presented in Tables 1 and 2. A year and plant density had more significant main effects than varieties on DTM, NPB, HFN, Plh, and IL of faba bean (Table 1) while their effects were more or less comparable on SP, NPPP, NSPP, HSW, BM, GY, SY, and HI (Table 2). Year-by-variety interaction influences were higher than those of plant density by variety interaction on DTF, Plh, IL, and BRR (Table 1), which also showed a similar trend on SP, NPPP, HSW, BM, and SY (Table 2). Year by variety by plant density interaction effects significantly ($p<0.01$) affected only DTF, NPB, SP, and NPPP among the 16 parameters indicated in Tables 1 and 2.

Table 1: Mean squares of ANOVA for phenological- and growth parameters and black root rot disease score of faba bean as affected by plant density and varieties of different seed size at Enewarie, combined over two years

Source	DTE	DTF	DTM	NPB	HFN	Plh	IL	BRR
Year (yr)	1.51^{ns}	320.00**	1522.51**	0.67*	2871.61**	1704.78**	14.62**	5.78*
Rep (yr)	1.8	1.33	3.31	0.12	21.03	11.13	0.51	0.96
Variety (var)	27.61**	328.05^{ns}	714.01^{ns}	0.90^{ns}	357.44*	694.43^{ns}	3.96^{ns}	75.08**
Plant density (pd)	4.89*	16.72^{ns}	69.98*	1.09**	758.42**	345.31**	1.40*	0.83^{ns}
yr*var	0.31^{ns}	28.80**	49.61**	0.99**	6.90^{ns}	986.31**	3.87**	14.03**
yr*pd	1.08^{ns}	2.84**	8.92*	0.03^{ns}	282.61**	242.81**	0.44*	0.84^{ns}
var*pd	1.36^{ns}	2.21^{ns}	13.73**	0.07*	38.33^{ns}	13.58^{ns}	0.06^{ns}	0.38^{ns}
yr*var*pd	0.63^{ns}	4.33**	0.89^{ns}	0.53**	85.89^{ns}	43.49^{ns}	0.16^{ns}	1.28^{ns}
Residual	1.333	0.695	3.248	0.021	50.226	56.218	0.126	0.554

ffi DTE=Days to 50% emergence; DTF=Days to 50% flower; DTM=Days to 90% physiological maturity; NPB=Number of primary branches; HFN=Height of first pod bearing node; Plh=Plant height; IL=Internode length; BRR=Black root rot score; ns = not significant at 5%

Table 2: Mean squares of ANOVA for yield, yield components, and harvest index of faba bean as affected by plant density and varieties of different seed size at Enewarie, combined over two years

Source	SP	NPPP	NSPP	HSW	BM	GY	SY	HI
Year (yr)	257.83^{ns}	141.25*	0.78*	3376.75**	44.77**	1.45*	62.33**	0.38**
Rep (yr)	227.42	22.02	0.1	17.74	0.720	0.23	0.29	0.002
Variety (var)	2570.33**	107.42^{ns}	0.99**	19767.90**	20.19*	0.75**	13.15*	0.01*
Plant density (pd)	1780.26**	179.92**	0.29^{ns}	20.17^{ns}	9.50*	0.74**	5.48*	0.01*
yr*var	580.29**	74.69**	0.01^{ns}	88.94*	10.02**	0.10^{ns}	8.12**	0.01^{ns}
yr*pd	451.58**	12.09^{ns}	0.20^{ns}	22.55^{ns}	2.37**	0.07^{ns}	2.14**	0.001^{ns}
var*pd	55.07^{ns}	9.18^{ns}	0.12^{ns}	20.97^{ns}	1.42ns	0.27*	0.48^{ns}	0.002^{ns}
yr*var*pd	268.68**	34.07**	0.10^{ns}	20.57^{ns}	0.39ns	0.22^{ns}	0.56^{ns}	0.005^{ns}
Residual	39.937	8.269	0.079	13.023	0.641	0.101	0.4093	0.003

ffi SP=Stand percent; NPPP=Number of pods per plant; NSPP=Number of seeds per pod; HSW=Hundred seeds weight; BM=Biomass yield; GY=Grain yield; SY=Straw yield; HI=Harvest index; ns = not significant at 5%

Depending on the significant interaction of variety and plant density effect on grain yield (Table 2), stepwise regression with a 5% probability level to enter and retain terms for grain yield of each variety revealed that no term was fit to make a response curve equation. However, variety *Lallo* showed quadratic response with the probability level of p = 0.1177 for the linear term, and p = 0.0182 for the quadratic term with the total R^2 value of 0.9861; the equation being:

Grain yield (t ha^{-1}) of *Lallo* = $2.214+0.01315-0.0000875P^2$; where P is plant density. This scenario shows that it is not dependable to estimate agronomic and economic optimum plant density based on the curve fit since we have no significantly acceptable curve fit for the two varieties. Thus, running a partial budget analysis based on the observed value of each plant density is the feasible option.

Since there is no significant variety by plant density interaction for straw yield (Table 2), both varieties showed a positively linear response at a probability of 1%. The response curve equations are:

- Straw yield (t ha^{-1}) of variety *Hachalu* = $1.395+0.02235P$; $R^2 = 1.0000$; and
- Straw yield (t ha^{-1}) of variety *Lallo* = $2.755+0.01315P$; $R^2 = 1.0000$; where P is plant density.

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As indicated in Table 3, variety *Lallo* emerged significantly earlier ($p<0.05$) than variety *Hachalu*. The variation might be related to genotypic differences. In line with this result, Asrat *et al*. (2003) reported varietal differences of soybean on days to 50% emergence. Although there was no significant difference between the varieties, the variety *Hachalu* flowered earlier by 4.1 days probably due to the incidence of black root rot disease which created stress that might have enhanced early flowering. However, at normal conditions, large-seeded genotypes meant to flower later than small-seeded faba bean genotypes (Salem 2007). According to Kemal and Rebecca (2016), biotic stress factors such as attacks by pests and pathogens can have a significant effect on plant development including flowering. For example, in *Arabidopsis* infection by *Verticillium* spp., which causes vascular wilt disease, delays flowering in some *A. thaliana* ecotypes but accelerates flowering in others. Variety *Lallo* produced significantly the highest height from the ground to the first pod-bearing node. The difference could be related to their flowering time as it was reported that late flowering faba bean genotypes showed higher height from ground to first pod-bearing nodes, while plants early in flowering showed lower stalk height to the first pod-bearing node. One of these reports by Talal and Munqez (2013) showed the stalk height from the ground to the first pod-bearing node of tested faba bean accessions ranged from 6.67 to 58.33 cm.

The highest stand percent of more than 15.37% (Table 4) was recorded for variety Lallo, which might be attributed to the death of more plants in variety Hachalu due to the highest black root rot incidence (Table 3). Although there was no significant difference among the varieties, the small-seeded variety Lallo produced the highest number of pods per plant. Yucel (2013) found that small-seeded faba bean varieties produced more pods (9.8) per plant than large-seeded faba bean varieties due to genotypic differences. The number of seeds per pod varied significantly between varieties because the number of seeds is determined more by genotype than by environmental conditions (Lopez-Bellido *et al* 2005). The large-seeded variety Hachalu gave significantly the highest hundred seed weight (more than 121.06%) over the small-seeded variety Lallo. According to Yucel (2013), due to a decrease in assimilates, small seeds produce less seed weight. The small seed variety Lallo gave significantly the highest biomass of 19.38% over the large seed variety Hachalu (Table 4), which could be attributable to the tallest plant height and the highest stand percent of variety Lallo (Tables 3 and Table 4). In line with this result, Bakry et al (2011) reported significant differences in the above-ground dry biomass among cultivars due to their highest plant height, the highest number of branches per plant, and different genetic makeup, which affect growth habit. Consequently, variety Lallo produced significantly the highest straw yield, with a 29.67% increase over that of variety Hachalu (Table 4). However, variety Hachalu showed higher partitioning of dry matter into grain yield by producing higher harvest index (Table 4). Bakry et al (2011) also reported a significantly highest harvest index for large-seeded faba bean varieties (23.23%) than medium seeded ones (18.78%). The black root rot incidence was significantly severe on variety Hachalu than on variety Lallo (Table 3). Their history from variety registration also indicates that variety Lallo is more tolerant to root rot and is specifically recommended for heavy Vertisols areas whereas variety Hachalu is meant for wider adaptation on Vertisols.

Table 3: Main effects of faba bean varieties on phenological and growth parameters, and black root rot disease score at Enewarie, combined over two years

Variety	DTE	DTF	DTM	NPB (sqrt)	HFN (cm)	IL (cm)	Plh (cm)	BRR (1-9)
Hachalu (Large seeded)	9.7^{a}	47.8	132.7	0.70(1.08)	34.8^{b}	3.1	76.6	3.9^{a}
Lallo (Small seeded)	8.5^{b}	51.9	126.7	0.49(0.98)	39.0^{a}	3.5	82.5	2.0^{b}
LSD (%)	0.52	ns	ns	ns	3.18	ns	ns	0.334
CV (%)	12.7	1.67	1.39	7.02	19.19	10.71	9.43	25.39

ffi DTE=Days to 50% emergence; DTF=Days to 50% flower; DTM=Days to 90% physiological maturity; NPB=Number of primary branches; sqrt=SHFN=Height of first pod bearing node; IL=Internode length; Plh=Plant height; BRR=Black root rot score; ns = not significant at 5%

Table 4: Main effects of faba bean varieties on yield and yield components at Enewarie, combined over two years

Variety	SP (%)	NPPP	NSPP	HSW (g)	BM (t ha^{-1})	GY (t ha^{-1})	SY (t ha^{-1})	HI
Hachalu (Large seeded)	73.71^{b}	12.8	2.2^{b}	57.41^{a}	5.16^{b}	2.42^{b}	2.73^{b}	0.49^{a}
Lallo (Small seeded)	85.04^{a}	15.1	2.4^{a}	25.97^{b}	6.16^{a}	2.62^{a}	3.54^{a}	0.47^{b}
LSD (%)	2.83	ns	0.13	1.62	0.359	0.142	0.29	0.024
CV (%)	7.96	20.64	12.31	8.66	14.15	12.60	20.37	11.24

ffi SP=Stand percent; NPPP=Number of pods per plant; NSPP=Number of seeds per pod; HSW=Hundred seeds weight; BM=Biomass yield; SY=Straw yield; HI=Harvest index

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Days to emergence increased by 15.12% as plant density decreased from 100 to 40 plants m^{-2} (Table 5), which might be attributed to higher seed rates exerting a higher force to overcome the force of the sticky Vertisols in order to emerge earlier than lower seed rates. This needs further study to confirm. Our results disagree with Lopez-Bellido et al (2005), who reviewed and reported that the seed germination and establishment rate of faba bean are not affected by increasing the sowing rate, except where different weather conditions or poor seed quality that led to losses in germination and seedling emergence that are greater at higher sowing rates. Khalil *et al* (2010) who studied the effect of plant densities of 150,000, 300,000, 450,000, and 600,000 plants ha^{-1} for one cultivar of faba bean also reported that plant density had no significant effect on days to emergence. However, because these studies did not specify the type of soil used, they cannot be considered universal, as soil type has a significant impact on emergence rate and time. Although not significant, days to flowering showed a decreasing trend as plant density increased from 20 to 100 plants m^{-2} (Table 5) which was probably due to higher plant-to-plant competition for growth factors that finally enhanced early flowering at higher densities. Khalil et al (2010) reported maximum days to flowering (54.2) for 150,000 plants ha^{-1} while minimum days to flowering (52.5 days) for 600,000 plants ha^{-1} of faba bean. As plant density increased from 20 to 100 plants per m^{-2}, the height of the first pod bearing node and internode length increased by 67.7% and 28.6%, respectively (Table 5). Similarly, plant height increased by 16.6% as plant density increased from 20 to 80 plants m^{-2} (Table 5). Yucel (2013), and Getachew and Missa (2011) also reported that the denser plant population increased the plant height due to competition among plants for light. Our study also indicated that there was a highly significant positive correlation between internodes length and plant height (Table 6).

Stand percent decreased by 41.26% as plant density increased from 20 to 100 plants m^{-2} which was probably due to mortality of plants caused by root rot incidence and plant-to-plant competition (Table 7). In line with this result, Lopez-Bellido *et al* (2005) reported that once emergence has taken place, excessive reduction of intra-row spacing leads to greater mortality due to increased plant-to-plant competition. Our study data also showed a significantly negative correlation between stand percent and black root rot incidence (Table 6). The number of pods per plant decreased by 48.92% as plant density increased from 20 to 100 plants m^{-2} (Table 7). Bakry *et al* (2011) reported a gradual decrease in the number of pods per plant of faba bean by increasing plant density from 16 to 42 plants m^{-2} which was probably due to increased competition among plants for growth factors, which finally reduced the number of effective branches. Our study also shows that there was a positive significant correlation between the number of pods per plant with each of days to flower, days to mature, stand percent, and a number of primary branches (Table 6). Changing plant density in our study had no significant effect on the number of seeds per pod and seed weight since these are mainly genotyped dependent. These results are in line with Getachew and Missa (2011), who reported that changing plant densities had no significant effect on the number of seeds per pod and 100 seeds weight of faba bean. Biomass yield increased by 44.37% as plant density increased from 20 to 100 plants m^{-2} (Table 7). This could be attributed to the increase in the number of plants per unit area and the associated increase in plant height which might compensate for side branches. It showed a positive significant correlation with the height of the first pod bearing node, plant height, and internodes length while negative significant correlation with black root rot incidence (Table 6). Our study results are in agreement with Getachew and Missa (2011) who reported a linear and significant increase in biomass as plant density increased from 30 to 60 plants m^{-2} on light *Vertisols*. Similarly, Mekkei (2014), Bakry *et al* (2011), and Dahmardeh *et al* (2010) reported higher dry matter production at higher densities across a wide range of seeding rates tested in both temperate and Mediterranean conditions. Similarly, straw yield increased by 62.61% as plant density increased from 20 to 100 plants m^{-2} (Table 7). In agreement with this result, Rifaee *et al* (2004) obtained the highest straw yield from the highest population (100 and 150 plants m^{-2}) due to less partitioning into grain yield. Our study also showed a positive significant correlation between straw yield and each height of the first pod bearing node, plant height, internodes length, and biomass while the negative significant correlation was with days to maturity and black root rot incidence (Table 6). Harvest index decreased by 15.91% as plant density increased from 40 to 100 plants m^{-2} (Table 7) probably due to higher plant-to-plant competition at higher plant densities for resources such as moisture, nutrients, and light which might favor higher total dry matter production than grain yield. In line with this result, Lopez-Bellido *et al* (2005) noted that for most crops under favorable conditions, dry matter production increases with density to a plateau above which inter-plant competition limits any further production. Thereafter, the harvest index tends to decline and seed yield often displays a negative response to increasing sowing rates. According to the review by Lopez-Bellido *et al* (2005), a number of authors place the upper limit for HI in faba beans at around 50%.

Table 5: Main effects of plant density on phenological and growth parameters, and black root rot disease score of faba bean at Enewarie, combined over two years

Plant density (m^{-2})	DTE	DTF	DTM	NPB (sqrt)	HFN (cm)	IL (cm)	Plh (cm)	BRR (1-9)
20	9.5^{ab}	51.5	132.9^{a}	$1.0(1.2)^{a}$	26.3^{c}	2.8^{c}	72.4^{c}	2.8
40	9.9^{a}	50.1	130.5^{b}	$0.7(1.1)^{b}$	36.1^{b}	3.3^{b}	78.7^{b}	2.7
60	8.9^{bc}	49.5	$129.3b^{c}$	$0.4(1.0)^{c}$	36.4^{b}	3.3^{b}	79.5^{ab}	3.1
80	8.7^{bc}	49.6	$128.3d^{c}$	$0.6(1.0)^{b}$	41.7^{a}	3.5^{ab}	84.4^{a}	2.8
100	8.6^{c}	48.7	127.6^{d}	$0.3(0.9)^{d}$	44.1^{a}	3.6^{a}	82.7^{ab}	3.2
LSD (%)	0.82	ns	1.277	0.051	5.024	0.252	5.315	ns
CV (%)	12.7	1.67	1.39	7.02	19.19	10.71	9.43	25.39

ffi DTE=Days to 50% emergence; DTF=Days to 50% flower; DTM=Days to 90% physiological maturity; NPB=Number of primary branches; HFN=Height of first pod bearing node; IL=Internode length; Plh=Plant height; BRR=Black root rot score

Table 6: Correlation coefficients between studied parameters of faba bean grown on *Vertisols* at Enewarie

	DTE	DTF	DTM	SP	NPB	NPPP	NSPP	HFN	Plh	IL	BRR	HSW	HI	BM	SY	GY
DTE	-															
DTF	-0.095ns	-														
DTM	0.395**	0.208ns	-													
SP	-0.095ns	0.262*	-0.150ns	-												
NPB	0.284*	0.169ns	0.484**	0.097ns	-											
NPPP	0.175ns	0.548**	0.279*	0.360**	0.636**	-										
NSPP	0.013ns	0.444**	0.112ns	0.140ns	-0.133ns	0.051ns	-									
HFN	-0.263*	-0.391**	-0.684**	-0.166ns	-0.473**	-0.437**	-0.088ns	-								
Plh	-0.239*	-0.164ns	-0.684**	-0.034ns	-0.323**	-0.194ns	-0.028ns	0.747**	-							
IL	-0.226*	-0.240*	-0.801**	-0.046ns	-0.429**	-0.319**	-0.058ns	0.738**	0.838**	-						
BRR	0.223*	-0.379**	0.569**	-0.432**	0.169ns	-0.218ns	-0.204ns	-0.340**	-0.542**	-0.536**	-					
HSW	0.456**	-0.301**	0.740**	-0.385**	0.414**	-0.072ns	-0.189ns	-0.431**	-0.409**	-0.519**	0.714**	-				
HI	0.278*	0.429**	0.732**	0.067ns	0.365**	0.329**	0.217ns	-0.579**	-0.539**	-0.704**	0.240*	0.443**	-			
BM	-0.326**	-0.227*	-0.752**	-0.049ns	-0.443**	-0.329**	-0.087ns	0.671**	0.729**	0.764**	-0.483**	-0.504**	-0.739**	-		
SY	-0.310**	-0.309**	-0.803**	-0.070ns	-0.431**	-0.339**	-0.110ns	0.694**	0.711**	0.807**	-0.445**	-0.533**	-0.867**	0.957**	-	
GY	-0.144ns	0.193ns	-0.053ns	0.055ns	-0.162ns	-0.062ns	0.102ns	0.118ns	0.263*	0.081ns	-0.257*	-0.051ns	0.194ns	0.416**	0.136ns	-

ffi DTE=Days to 50% emergence; DTF=Days to 50% flower; DTM=Days to 90% physiological maturity; SP=Stand percent; NPB=Number of primary branches; NPPP=Number of pods per plant; NSPP=Number of seeds per pod; HFN=Height of first pod bearing node; Plh=Plant height; IL=Internode length; BRR=Black root rot score; HSW=Hundred seeds weight; HI=Harvest index; BM=Biomass yield; GY=Grain yield; SY=Straw yield; ns = not significant at 5%

Table 7: Main effects of plant density on yield and yield components of faba bean grown on *Vertisols* at Enewarie, combined over two years

Plant density (m^{-2})	SP (%)	NPPP	NSPP	HSW (g)	BM (t ha^{-1})	GY (t ha^{-1})	SY (t ha^{-1})	HI
20	93.02^{a}	18.6^{a}	2.3	42.8	4.44^{c}	2.14^{b}	2.30^{c}	0.50^{ab}
40	84.16^{b}	15.3^{b}	2.3	41.0	5.57^{b}	2.58^{a}	2.99^{b}	0.51^{a}
60	81.46^{b}	13.5^{bc}	2.3	42.9	5.65^{b}	2.63^{a}	3.01^{b}	0.49^{ab}
80	72.39^{c}	12.7^{c}	2.2	41.4	6.23^{a}	2.57^{a}	3.66^{a}	0.46^{bc}
100	65.85^{d}	9.5^{d}	2.2	40.4	6.41^{a}	2.67^{a}	3.74^{a}	0.44^{c}
LSD (5%)	4.48	2.04	ns	ns	0.568	0.225	0.454	0.04
CV (%)	7.96	20.64	12.31	8.66	14.15	12.60	20.37	11.24

ffi SP=Stand percent; NPPP=Number of pods per plant; NSPP=Number of seeds per pod; HSW=Hundred seeds weight; BM = Biomass yield; GY = Grain yield; SY=Straw yield; HI=Harvest index; ns = not significant at 5%

ffi ffb ffi ffffb fb flffi ffi ffi ffi ffi

The lowest number of days to 90% physiological maturity for the large-seeded variety *Hachalu* was 130.7 days under plant density of 100 plants m^{-2} while that of the small seed variety *Lallo* was 124.4 days under plant density of 80 plants m^{-2} (Table 8). In the first year, both varieties matured earlier than their normal maturity time of 122-156 days and 158 days for variety *Hachalu* and *Lallo*, respectively (MoA 2014) (individual analysis not shown). Reduction in maturity days probably occurred due to late sowing (in the first year due to late-onset and lower amount of rainfall) (Figure 1) and desiccating wind which affected the normal physiological maturity of the crop. It was more pronounced on small-seeded variety (especially at higher plant densities). Lopez-Bellido *et al* (2005) also noted that high densities accelerate the maturity of the crop. Both varieties produced significantly the highest number of primary branches per plant (1.13 for *Hachalu*, and 0.88 for *Lallo* under the lowest plant density of 20 plants m^{-2} although the number of branches per plant in *Hachalu* was significantly higher than that of *Lallo* in all plant densities except at 40 plants m^{-2} (Table 8). In agreement with this result, Yucel (2013) and Bakry *et al* (2011) reported that cultivar difference showed a significant effect on the number of side branches probably due to the different genetic makeup while the decrease in branch number by increasing plant density could be attributed to high competition between plants in the same unit area.

Grain yield of 2.44 t ha^{-1} from variety *Lallo* at a plant density of 20 plants m^{-2} was significantly higher than that of 1.84 t ha^{-1} from variety *Hachalu* at the same density (Table 8). All grain yields ranging from 2.61-2.72 t ha^{-1} from planting density of 40-100 plants m^{-2} for variety *Lallo* were not significantly different from that of 20 plants m^{-2}; but the grain yield of 2.42-2.69 t ha^{-1} from plant density of 40-100 plants m^{-2} for variety *Hachalu* was significantly different from that of 20 plants m^{-2} (Table 8). According to Al-Suhaibani (2013), the optimum plant density to obtain high productivity for different faba bean varieties can range from 10 to 100 plants m^{-2}. However, Graf and Rowland (1987), cited in Al-Suhaibani (2013) 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 8: Two-way interaction effects of faba bean varieties with plant densities on physiological maturity, number of primary branches, and grain yield at Enewarie, combined over two years

ffi	ffi				
	20	40	60	80	100
			ffb		
Hachalu	134.4e	133.7de	132.5cde	132.2cd	130.7c
Lallo	131.5c	127.2b	126.1ab	124.4a	124.5a
		LSD (%)=1.80, Mean=129.7 , CV(%)=1.39			
		flffi	fb ffbffi ffi		
Hachalu	1.13a	0.66cd	0.54de	0.75bc	0.44ef
Lallo	0.88b	0.65cd	0.35f	0.39ef	0.19g
		LSD (%)= 0.15, Mean= 0.6, CV(%)= 24.9			
			ffi		
Hachalu	1.84b	2.55a	2.61a	2.42a	2.69a
Lallo	2.44a	2.61a	2.67a	2.72a	2.65a
		LSD (%)=0.33, Mean=2.52, CV(%)=12.60			

ffi LSD = Least significant difference; CV= Coefficient of variation; Means of each parameter in column and row followed by the same letters are not significantly different at 5%

ffb ffb

Since the interaction between faba bean varieties and plant densities was significant, a separate economic analysis was performed for each variety on mean grain- and straw yield based on the procedures indicated in CIMMYT (1988). Accordingly, for the large-seeded faba bean variety Hachalu, the highest net benefits of 30248.10 ETB ha^{-1} with a marginal rate of return of 281.40% were obtained under a plant density of 40 plants m^{-2} (a seed rate of 297.8 kg ha^{-1}) while all other higher planting densities were dominated (Table 9). Similarly, for the small-seeded faba bean variety Lallo, the highest net benefits of 28408.09 ETB ha^{-1} with a marginal rate of return of 120.09% were obtained under a plant density of 40 plants m^{-2} (a seed rate of 139.4 kg ha^{-1}) while all other higher planting densities were dominated (Table 10). Although the two varieties have the same recommendable planting density, the net benefit and marginal rate of return are higher for the large-seeded faba bean variety Hachalu because of its larger seed size associated with a higher price in the local market.

Table 9: Dominance and marginal rate of return analysis for grain and straw yield of faba bean variety *Hachalu* as affected by planting densities at Enewarie, combined over two years

Plant density m^{-2}	Observed grain yield (t ha^{-1})	Observed straw yield (t ha^{-1})	Adjusted grain yield (t ha^{-1})	Adjusted straw yield (t ha^{-1})	GB (ETB ha^{-1})	TVC (ETB ha^{-1})	NB (ETB ha^{-1})	MRR (%)
20 (148.9 kg ha^{-1})	1.84	1.63	1.66	1.47	25385.90	2680.41	22705.40	
40 (297.8 kg ha^{-1})	2.55	2.58	2.30	2.32	35609.00	5360.82	30248.10	281.4
60 (446.7 kg ha^{-1})	2.61	2.70	2.35	2.43	36529.70	8041.24	28488.40	D
80 (595.6 kg ha^{-1})	2.42	3.24	2.18	2.92	34864.70	10721.70	24143.00	D
100 (744.6 kg ha^{-1})	2.69	3.53	2.42	3.18	38658.20	13402.10	25256.10	D

ffi GB= Gross benefit; TVC= Total variable cost; NB= Net benefit; MRR= Marginal rate of return; D= Dominated

Table 10: Dominance and marginal rate of return analysis for grain and straw yield of faba bean variety *Lallo* as affected by planting densities at Enewari, combined over two years

Plant density (m^{-2})	Observed grain yield (t ha^{-1})	Observed straw yield (t ha^{-1})	Adjusted grain yield (t ha^{-1})	Adjusted straw yield (t ha^{-1})	GB (ETB ha^{-1})	TVC (ETB ha^{-1})	NB (ETB ha^{-1})	MRR (%)
20 (69.7 kg ha^{-1})	2.44	2.97	2.20	2.67	28205.1	1010.45	27194.65	
40 (139.4 kg ha^{-1})	2.61	3.40	2.35	3.06	30429.0	2020.91	28408.09	120.1
60 (209.1 kg ha^{-1})	2.67	3.32	2.40	2.99	30915.0	3031.36	27883.64	D
80 (278.7 kg ha^{-1})	2.72	4.09	2.45	3.68	32449.5	4041.81	28407.69	D
100 (348.4 kg ha^{-1})	2.65	3.95	2.39	3.56	31567.5	5052.26	26515.24	D

ffi GB= Gross benefit; TVC= Total variable cost; NB= Net benefit; MRR= Marginal rate of return; D= Dominated

H H

Our study revealed that the two faba bean varieties (large and small-seeded) responded differently to the changes in plant density for grain yield and some agronomic parameters considered. ANOVA results showed the highest grain yields for plant densities of 100 and 80 plants m^{-2} for the varieties Hachalu and Lallo, respectively. Although the two varieties have the same recommendable planting density of 40 plants m^{-2} in row planting, the net benefit and marginal rate of return are higher for variety Hachalu because of its larger seed size associated with a higher price in the local market. This variety also has a good future to meet the large seed size demands of export markets. Therefore, a planting density of 40 plants m^{-2} in 40 cm spaced rows is recommended for the production of the large-seeded faba bean variety Hachalu with a matching seed rate of about 298 kg ha^{-1} on relatively light Vertisols and the small-seeded faba bean variety Lallo with a matching seed rate of about 139 kg ha^{-1} on heavy Vertisols in the highlands of North Shewa and similar areas. We have also observed that higher seed rates enhance emergence and maturity, which are important for further research to improve frost escape mechanisms in high-altitude areas where frost is a problem.

H S

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W W H

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