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# INFLUENCE OF VARIED PLANT DENSITY ON GROWTH, YIELD AND ECONOMIC RETURN OF DRIP IRRIGATED FABA BEAN (*Vicia faba* L.)

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**ABSTRACT**

**Faba bean frequently alter the structure and size of their canopy as a consequence of environmental factors. This peculiarity has been taken into account to handle the little information regarding how growth and yield of faba bean respond to significant changes in plant density and how these changes affect yield potential and economic return. The seeds of two faba bean varieties (Giza 716 and Giza 843) were cultivated around the emitters of a drip irrigation system at five densities (4, 6, 8, 10 and 12 plants dripper$^{-1}$). The results showed that the relative growth rate, net assimilation rate, total dry weight per plant and leaf area per plant gradually increased with increasing plant density up to 8 plants dripper$^{-1}$ and significantly decreased with 10 and 12 plants dripper$^{-1}$; however, increasing plant density increased the plant height and decreased the number of branches per plant. The highest leaf area duration and leaf area index were found at 8 plants dripper$^{-1}$, while the lowest were found at 4 plants dripper$^{-1}$. While yield components of individual plants tend to significantly decrease with increased plant density, seed yield per hectare significantly increased with increasing plant density up to 8 plants dripper$^{-1}$ and slightly decreased with 10 and 12 plants dripper$^{-1}$. Crop production functions with respect to the number of plants per dripper versus all the attributes measured exhibited strong quadratic relationships with the exception of the yield components of individual plants, which exhibited a strong linear relationship. Seed yield per hectare showed a strong relationship with crop growth and vegetative growth parameters but not with the yield components of individual plants. Finally, when the plant densities were converted to seeding rates, simulations indicated that 118.0 (6 plants dripper$^{-1}$) and 118.8 kg ha$^{-1}$ (8 plants dripper$^{-1}$) for branched (Giza 716 ) and non-branched (Giza 843) varieties, respectively, were adequate to lower seed cost without reducing net profit.**

**Keywords: Competition, lateral spacing, seeding rate, seed yield, yield components**

## INTRODUCTION

Plant density defines the number of plants per square meter, which in turn determines the area available to each individual plant. For most crops, plant density has a major influence on biomass, crop yield and economic profitability (Rafiei, 2009; Albayrak et al., 2011; Ciampitti and Vyn, 2011). In faba bean, according to Loss et al. (1998), plant density can affect canopy architecture, light conversion efficiency, duration of vegetative growth, dry matter production, seed yield and ultimately, the economic productivity of a crop. Therefore, optimising plant density, which may be defined by both the number of plants per unit area and the arrangement of plants on the ground, is a pre-requisite for obtaining higher productivity of faba bean. This is because the number of plants per unit area is an important determinant of final seed yield, it is the first yield component to be established at the early crop cycle, it is largely dictated and controlled by the farmer himself, and finally, it is largely unaffected by environmental change (Dantuma and Thompson, 1983). However, other yield components such as number and weight of pods and seeds per plant and 100 seed weight which are established at a later stage in the course of the crop cycle are significantly affected by environmental conditions. Furthermore, the contribution efficiency of these components in the final seed yield is also associated with the number of plants per unit area (López-Bellido et al., 2005). Therefore, varying plant density may be a viable alternative of manipulating the productivity of faba bean under different environmental conditions through their changes in physiological processes.

The available literature pertaining to the response of faba bean to plant density indicates that a wide range of densities is commonly used (Bianchi, 1979; Caballero, 1987; Pilbeam et al., 1991; Almeida et al., 1995; Loss et al., 1998; López-Bellido et al., 2005; Mathews et al., 2008; Khalil et al, 2010; Ragab et al., 2010; Bakry et al., 2011). According to the literature, the optimum plant density to obtain high productivity for different faba bean crop varieties can range from 10 to 100 plants m$^{-2}$. These finding indicate that the faba bean crop has the ability to alter plant size and canopy structure in response to changes in plant density. In addition, 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 (Graf and Rowland, 1987). Unfortunately, studies about the optimum plant densities have been conducted when faba bean is cultivated by conventional practices. In such practices, the faba bean seeds are sown in rows, raised beds or ridges with different intra-plant and inter-plant competition. To date, no extensive studies have investigated the optimum plant density when faba bean is grown using a drip irrigation system. Drip irrigation system has a unique capacity to allow different plant distributions around the emitters and has many advantages in the cultivation of field row crops in arid and semiarid regions. However, the main limitation of applying this system to growing field crops is that the initial installation costs have been considered prohibitive for field row crops. Among the various components of a drip system, laterals costs (constituting more than 35% of the total cost of the system) play an important role in determining the cost of the system for annual and closely spaced crops such as faba bean. Because many vegetable crops are grown at lateral spacing of 1.4 m or more with an emitter spacing of 0.3–0.5 m, using such a design could be one of the most significant factors in reducing the overall investment costs of drip irrigation when it is used for field crop production. Furthermore, such design may be considered for faba bean production through crop rotation with vegetable crops. However, information on planting arrangement around emitters with large spacing between laterals, which creates significant intra-plant competition without any inter-plant competition, has not been investigated. Therefore, the objective of this study was to investigate the influence of different plant distribution patterns around the emitters of drip irrigation systems which creates only one competition between plants on growth, yield and economic return of two varieties of faba bean.

## MATERIALS AND METHODS

### *Experimental site description*

This study was conducted at the Experimental Farm of the Faculty of Agriculture at Suez Canal University, Ismailia, Egypt (30º58′ N latitude, 32º23′ E longitude and 13 m above sea level) during the winter seasons of 2011 and 2012. The soil texture of the experimental site is predominantly sandy throughout its profile (65.2% coarse sand, 26.9% fine sand, 4.6% silt and 3.3% clay) with an EC of 0.52 dSm$^{-1}$ and a pH of 7.85.

### *Experimental design and treatments*

A randomised complete block split-plot design with three replicates was used in each season. Varieties and plant densities were randomly assigned to the main and split plots, respectively. A layout of the experimental plots is shown in Fig.1. The drip irrigation system, with a design to reduce the high overall investment costs of drip irrigation systems, was divided into two main sectors with the two varieties of faba bean (Giza 716 and Giza 843) assigned to the two sectors. Within each sector, there were three replicates of the same variety.

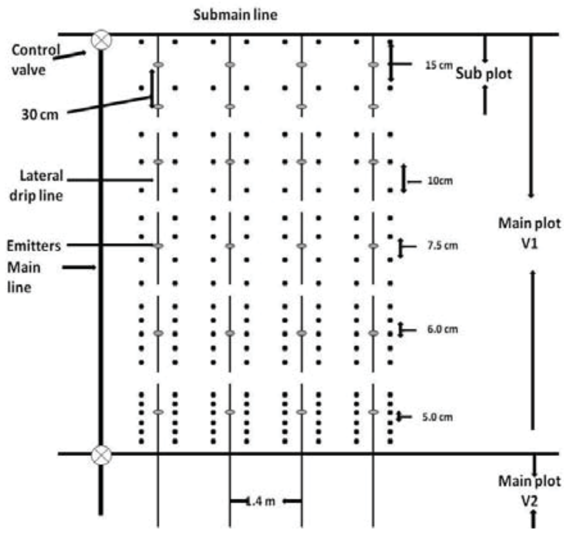


**Fig. 1.** Layout of one replicate of an experimental design that includes two varieties and five plant densities, showing locations of varieties and plant distributions around the emitters. 15, 10, 7.5, 6.0, and 5.0 cm indicated the distance between plants for 4, 6, 8, 10 and 12 plants dripper$^{-1}$ treatments, respectively.

Five plant densities (4, 6, 8, 10 and 12 plants dripper$^{-1}$) were randomly nested within each main plot of each variety as a split plot. Each split plot consisted of five polyethylene lateral drip lines (Twin-wall IV, 16 mm in diameter, and 0.3 m emitter spacing) with a length of 5 m. The lateral line was laid out along each faba bean row at 1.4 m. The split plot area was 35 m$^2$. To achieve the desired plant densities, 15, 10, 7.5, 6.0 and 5.0 cm were left between seeds for 4, 6, 8, 10 and 12 plants dripper$^{-1}$, respectively (Fig 1).

### *Agronomic practices*

Seeds of faba bean varieties were sown on 15 October during both growing seasons. Before sowing, the seeds were inoculated with *Rhizobium leguminosarum* at the time of seeding. Therefore, a simulative dose of ammonium sulphate (20.5% N) (60 kg ha$^{-1}$) was added before the first irrigation. Phosphorus fertiliser was applied basally during seed-bed preparation at a level of 200 kg ha$^{-1}$ as calcium super phosphate (15.5% $P_2O_5$). Potassium fertiliser was applied at a level of 100 kg ha$^{-1}$ as potassium sulphate (48% $K_2O$) in one dose 40 days after sowing. Weed, pest, and disease control was performed in a timely manner. Hand harvesting was performed approximately 170 days after sowing.

*Parameter assessments*

At 70 and 100 days after sowing, 10 plants from each plot were harvested at random to determine the plant height, number of branches per plant, total dry weight per plant and leaf area per plant. Plant samples were separated into leaves and stems after the plant height was recorded. Leaf area was measured using a LI-3000 Area Meter (LI-COR, Walz Co., Lincoln, NE, USA). The leaf area index (LAI) was calculated by dividing the leaf area per plant by the area of ground occupied by the plant. After the leaf area was determined, the samples were dried in a forced-air oven at 75 °C for 72 h, and then their dry weights were determined. The total dry weight was obtained by the summation of the individual fractions.

Relative growth rate (RGR, g $g^{-1}$ $day^{-1}$), net assimilation rate (NAR, g $cm^{-2}$ $day^{-1}$) and leaf area duration (LAD, day) were derived using the following equations (Hunt, 1990):

$$RGR = 1/W \times \partial W/\partial T \quad (1)$$

$$NAR = 1/L_A \times \partial W/\partial T \quad (2)$$

$$LAD = ½ (LAI_1 + LAI_2) (T_2 - T_1) \quad (3)$$

where W, T, $L_A$ and LAI are plant dry weight (g), time (day), leaf area ($cm^2$) and leaf area index, respectively.

After physiological maturity at approximately 170 days after sowing, an additional 10 plants from each plot were harvested at random to determine the number and weight of pods and seeds per main stem and branches. Seed yield was determined by hand harvesting an area of three rows, each 5.0 m in length (21.0 $m^2$ in total area), from each plot. Seed samples were collected from the yield samples to determine the moisture content, and seed yield was adjusted to a moisture content of 15.5%.

*Economic return*

Following Graf and Rowland (1987), the plant populations were converted to seeding rates (kg $ha^{-1}$) by multiplying plant population by the average seed weight for each variety. To simulate seed costs of one, two or three times that of the product price, the seeding rates were multiplied by a factor of 1, 2 or 3, respectively. The resulting values were subtracted from the yield to give comparable net yields. Then, the net yield was converted to a relative scale by dividing by a maximum yield of 2800 kg $ha^{-1}$. Finally, the relationship between seeding rates and relative net yield at different plant densities was calculated, while the seed cost to product price ratio ranged from 0:1 to 3:1. The 0:1 ratio represents when the seed cost was equal to the product price. However, the 1:1, 1:2 or 3:1 ratio represents the seed being one, two or three times that of the product price, respectively.

*Statistical analysis*

All measurements in this study were analysed using an analysis of variance (ANOVA) appropriate for a randomised complete block split-plot design with two varieties as the main plot, plant density as the subplots and replicates as blocks. Treatment means were compared using Duncan's multiple test. Probability levels lower than 0.05 was considered significant. Statistical analyses were performed using SAS statistical analysis package (SAS institute, Inc., Cary, NC). Polynomial and linear regression analyses were performed to investigate the relationship between plant density and different parameters of growth and yield. Regression analyses were performed using Microsoft Excel 2007.

## RESULTS

*Effect of plant density, variety and their interaction on crop growth parameters*

The crop growth parameters, relative growth rate (RGR), net assimilation rate (NAR) and leaf area duration (LAD) were significantly affected by plant density. In both seasons, the highest RGR and NAR values were obtained at densities of 6 and 8 plants $dripper^{-1}$, followed by 4 plants $dripper^{-1}$, while 10 and 12 plants $dripper^{-1}$ produced the lowest values for both parameters (Table 1). Averaged over two seasons, planting with 10 and 12 plants $dripper^{-1}$ resulted in a significantly lower RGR by 34.8 and 47.3% and NAR by 38.8 and 47.9%, respectively, when compared to the medium plant density (8 plants $dripper^{-1}$). The differences in LAD between 6, 10 and 12 plants $dripper^{-1}$ were not significant, with the medium plant density (8 plants $dripper^{-1}$) and the low plant density (4 plants $dripper^{-1}$) producing the highest and lowest values for LAD, respectively(Table 1).

**Table 1.** Effects of varieties, plant population density and their interaction on the crop growth parameters relative growth rate (RGR), net assimilation rate ( NAR) and leaf area duration (LAD) in 2011 and 2012.

| | **2011** | | | **2012** | | |
|---|---|---|---|---|---|---|
| | **Giza 716 (V1)** | **Giza 843 (V2)** | **Mean** | **Giza 716 (V1)** | **Giza 843 (V2)** | **Mean** |
| **RGR (g g$^{-1}$ day$^{-1}$)** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 0.040 b | 0.041 b | 0.040 b | 0.040 b | 0.040 a | 0.040 b |
| $D_2$ (6 plants driper$^{-1}$) | 0.045 a | 0.044 a | 0.045 a | 0.043 b | 0.043 a | 0.043 a |
| $D_3$ (8 plants driper$^{-1}$) | 0.045 a | 0.046 a | 0.045 a | 0.047 a | 0.040 a | 0.043 a |
| $D_4$ (10 plants driper$^{-1}$) | 0.027 c | 0.030 c | 0.028 c | 0.026 c | 0.034 b | 0.030 c |
| D5 (12 plants driper$^{-1}$) | 0.024 c | 0.026 c | 0.025 c | 0.021 d | 0.022 c | 0.022 d |
| Mean | 0.036 a | 0.037 a | | 0.035 a | 0.036 a | |
| **NAR (g cm$^{-2}$ day$^{-1}$)** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 4.53 ab | 4.28 b | 4.40 b | 5.06 b | 4.93 b | 4.99 b |
| $D_2$ (6 plants driper$^{-1}$) | 4.68 a | 4.81 a | 4.75 a | 5.18 b | 5.48 a | 5.33 a |
| $D_3$ (8 plants driper$^{-1}$) | 4.56 a | 4.98 a | 4.77 a | 5.64 a | 5.13 a | 5.38 a |
| $D_4$ (10 plants driper$^{-1}$) | 2.56 c | 3.25 c | 2.90 c | 2.69 c | 3.95 c | 3.32 c |
| D5 (12 plants driper$^{-1}$) | 2.69 c | 3.08 c | 2.88 c | 2.35 d | 2.38 d | 2.36 c |
| Mean | 3.80 a | 4.08 a | | 4.18 a | 4.37 a | |
| **LAD (days)** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 63.7 c | 55.8 c | 59.8 c | 66.4 c | 56.1 c | 61.3 c |
| $D_2$ (6 plants driper$^{-1}$) | 88.8 b | 104.3 b | 96.6 b | 90.1 b | 107.1 b | 98.6 b |
| $D_3$ (8 plants driper$^{-1}$) | 114.2 a | 139.0 a | 126.6 a | 118.1 a | 142.0 a | 130.0 a |
| $D_4$ (10 plants driper$^{-1}$) | 85.3 b | 97.6 b | 91.4 b | 85.4 b | 110.1 b | 97.8 b |
| D5 (12 plants driper$^{-1}$) | 79.4 b | 97.9 b | 88.7 b | 86.1 b | 108.9 b | 97.5 b |
| Mean | 86.3 b | 98.9 a | | 89.2 b | 104.8 a | |

In a column, means with different letter denoted statistically difference between treatment groups according to Duncan's test ($P < 0.05$).

Although the differences between the two varieties in terms of RGR and NAR were not significant, the response of the two varieties to different plant densities was always significant with respect to these two parameters. However, the LAD for Giza 843 exceeded the values of Giza 716 by 12.7 and 14.9% in 2011 and 2012, respectively. Generally, for both varieties, the lowest RGR and NAR values were obtained at the high plant density (10 and 12 plants dripper$^{-1}$), but the influence of both densities on RGR and NAR for Giza 843 was less marked than that for Giza 716 (Table 1). The highest and lowest LAD values for both varieties was obtained at medium and low plant density, respectively, with no significant differences being detected between 6, 10 and 12 plants dripper$^{-1}$ (Table 1).

*Effect of plant density, variety and their interaction on vegetative growth parameters*

Results obtained over the 2-year study showed that the different vegetative growth parameters (i.e., plant height, number of branches per plant, total dry weight per plant, leaf area per plant and leaf area index) at 70 and 100 days after sowing were significantly affected by plant density (Tables 2 and3).The low plant density (4 plants dripper$^{-1}$) produced the lowest values for only two vegetative growth parameters (plant height and leaf area index) at two sampling times. Averaged over the two seasons, the low plant density resulted in decreases in plant height and in the leaf area index of 19.8 and 48.3% at 70 days after sowing and 35.8 and 25.4% at 100 days after sowing, respectively, when compared to the high plant density (12 plants dripper$^{-1}$), although the latter density decreased the branch number per plant by 46.0 and 54.3%,total dry weight per plant by 32.9 and 59.2% and leaf area per plant by 35.5 and 55.2%at 70 and 100 days after sowing, respectively, when compared to the low plant density. The highest total dry weight and leaf area per plant values at two sampling times were obtained at densities of 6 or 8 plants dripper$^{-1}$, which were not significantly different from one another (Tables 2 and 3).

**Table 2.** Effects of varieties, plant density and their combination on selected growth parameters at 70 days after sowing in 2011 and 2012

| | 2011 | | | 2012 | | |
|---|---|---|---|---|---|---|
| | **Giza 716 (V1)** | **Giza 843 (V2)** | **Mean** | **Giza 716 (V1)** | **Giza 843 (V2)** | **Mean** |
| **Plant height (cm)** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 50.8 b | 49.6 b | 50.2 b | 46.4 b | 46.3 c | 46.4 b |
| $D_2$ (6 plants driper$^{-1}$) | 52.7 b | 51.8 ab | 52.3 b | 51.0 b | 50.1 bc | 50.6 b |
| $D_3$ (8 plants driper$^{-1}$) | 59.3 a | 53.9 ab | 56.6 a | 62.0 a | 56.5 ab | 59.3 a |
| $D_4$ (10 plants driper$^{-1}$) | 59.4 a | 53.4 ab | 56.4 a | 64.7 a | 58.8 a | 61.8 a |
| D5 (12 plants driper$^{-1}$) | 60.4 a | 57.1 a | 58.8 a | 63.4 a | 60.2 a | 61.8 a |
| Mean | **56.5 a** | **53.2 a** | | **57.5 a** | **54.4 a** | |
| **Number of branches per plant** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 5.1 a | 2.4 a | 3.8 a | 5.7 a | 2.5 a | 4.1 a |
| $D_2$ (6 plants driper$^{-1}$) | 4.7 a | 2.5 a | 3.6 a | 5.1 a | 2.3 a | 3.7 a |
| $D_3$ (8 plants driper$^{-1}$) | 3.5 b | 2.2 a | 2.8 b | 3.7 b | 2.3 a | 3.0 b |
| $D_4$ (10 plants driper$^{-1}$) | 2.9 bc | 2.0 a | 2.5 bc | 3.6 bc | 2.0 a | 2.8 b |
| D5 (12 plants driper$^{-1}$) | 2.1 c | 1.7 a | 1.9 c | 2.7 c | 2.0 a | 2.4 b |
| Mean | **3.7 a** | **2.2 b** | | **4.2 a** | **2.2 b** | |
| **Total dry weight (g plant$^{-1}$)** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 12.7 a | 9.7 b | 11.2 a | 14.8 a | 12.1 b | 13.4 a |
| $D_2$ (6 plants driper$^{-1}$) | 9.7 b | 12.1 a | 10.9 a | 12.0 b | 14.8 a | 13.4 a |
| $D_3$ (8 plants driper$^{-1}$) | 9.2 b | 11.7 a | 10.5 a | 11.0 b | 15.8 a | 13.4 a |
| $D_4$ (10 plants driper$^{-1}$) | 7.3 c | 9.3 b | 8.3 b | 8.1 c | 10.2 c | 9.2 b |
| D5 (12 plants driper$^{-1}$) | 6.8 c | 8.8 b | 7.8 b | 8.0 c | 9.4 c | 8.7 b |
| Mean | 9.1 b | 10.3 a | | 10.8 b | 12.5 a | |
| **Leaf area per plant (cm$^2$)** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 1481.3 a | 1191.9 b | 1336.6 b | 1600.2 a | 1276.4 b | 1438.3 a |
| $D_2$ (6 plants driper$^{-1}$) | 1336.8 b | 1558.1 a | 1447.4 a | 1461.8 b | 1683.1 a | 1572.4 a |
| $D_3$ (8 plants driper$^{-1}$) | 1318.1 b | 1539.6 a | 1428.9 ab | 1424.8 b | 1606.2 a | 1515.5 a |
| $D_4$ (10 plants driper$^{-1}$) | 920.2 c | 1063.4 bc | 991.8 c | 840.2 c | 1130.0 bc | 985.1 b |
| D5 (12 plants driper$^{-1}$) | 800.0 c | 933.4 c | 866.7 d | 823.4 c | 1023.4 c | 923.4 b |
| Mean | 1171.3 b | 1257.3 a | | 1230.1 b | 1343.8 a | |
| **Leaf area index** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 1.41 d | 1.14 e | 1.27 d | 1.52 d | 1.22 d | 1.37 d |
| $D_2$ (6 plants driper$^{-1}$) | 1.91 c | 2.23 d | 2.07 c | 2.09 bc | 2.40 c | 2.25 c |
| $D_3$ (8 plants driper$^{-1}$) | 2.51 a | 2.93 a | 2.72 a | 2.71 a | 3.06 a | 2.89 a |
| $D_4$ (10 plants driper$^{-1}$) | 2.19 b | 2.53 c | 2.36 b | 2.00 c | 2.69 bc | 2.35 c |
| D5 (12 plants driper$^{-1}$) | 2.29 ab | 2.67 bc | 2.48 b | 2.35 b | 2.92 ab | 2.64 b |
| Mean | 2.06 b | 2.30 a | | 2.14 b | 2.46 a | |

In a column, means with different letter denoted statistically difference between treatment groups according to Duncan's test ($P < 0.05$).

**Table 3.** Effects of varieties, plant population density and their combination on selected growth parameters at 100 days after sowing in 2011 and 2012

| | 2011 | | | 2012 | | |
|---|---|---|---|---|---|---|
| | **Giza 716 (V1)** | **Giza 843 (V2)** | **Mean** | **Giza 716 (V1)** | **Giza 843 (V2)** | **Mean** |
| | | | **Plant height (cm)** | | | |
| $D_1$ (4 plants driper$^{-1}$) | 84.2 b | 83.6 b | 83.9 b | 80.8 c | 79.6 c | 80.2 d |
| $D_2$ (6 plants driper$^{-1}$) | 95.0 b | 89.0 b | 92.0 b | 88.3 c | 84.7 c | 86.5 d |
| $D_3$ (8 plants driper$^{-1}$) | 118.5 a | 111.7 a | 115.1 a | 117.8 b | 114.3 b | 116.1 c |
| $D_4$ (10 plants driper$^{-1}$) | 123.1 a | 115.6 a | 119.4 a | 126.4 ab | 119.0 b | 122.7 b |
| D5 (12 plants driper$^{-1}$) | 127.0 a | 119.1 a | 123.1 a | 135.3 a | 130.8 a | 133.1 a |
| Mean | 109.5 a | 103.8 a | | 109.7 a | 105.7 a | |
| | | | **Number of branches per plant** | | | |
| $D_1$ (4 plants driper$^{-1}$) | 6.0 a | 3.0 a | 4.5 a | 7.0 a | 3.4 a | 5.2 a |
| $D_2$ (6 plants driper$^{-1}$) | 5.1 ab | 3.0 a | 4.1 ab | 5.9 b | 3.4 a | 4.7 a |
| $D_3$ (8 plants driper$^{-1}$) | 4.2 bc | 2.3 a | 3.3 bc | 4.3 c | 3.0 a | 3.7 b |
| $D_4$ (10 plants driper$^{-1}$) | 3.3 cd | 2.2 a | 2.8 cd | 3.7 cd | 2.5 a | 3.1 bc |
| D5 (12 plants driper$^{-1}$) | 2.3 d | 1.7 a | 2.0 d | 2.9 d | 1.9 a | 2.4 c |
| Mean | 4.2 a | 2.5 b | | 4.7 a | 2.9 b | |
| | | | **Total dry weight (g plant$^{-1}$)** | | | |
| $D_1$ (4 plants driper$^{-1}$) | 41.8 a | 33.5 b | 37.6 b | 48.8 a | 39.8 b | 44.3 b |
| $D_2$ (6 plants driper$^{-1}$) | 37.6 b | 45.7 a | 41.6 a | 43.6 b | 54.4 a | 49.0 a |
| $D_3$ (8 plants driper$^{-1}$) | 35.4 b | 46.3 a | 40.9 a | 44.8 b | 52.3 a | 48.6 a |
| $D_4$ (10 plants driper$^{-1}$) | 16.3 c | 22.4 c | 19.4 c | 17.5 c | 28.0 c | 22.7 c |
| D5 (12 plants driper$^{-1}$) | 14.1 c | 19.1 d | 16.6 d | 15.0 c | 18.3 d | 16.6 d |
| Mean | 29.0 b | 33.4 a | | 33.9 b | 38.6 a | |
| | | | **Leaf area per plant (cm$^2$)** | | | |
| $D_1$ (4 plants driper$^{-1}$) | 2976.2 a | 2716.9 b | 2846.6 b | 3046.2 a | 2653.6 b | 2849.9 b |
| $D_2$ (6 plants driper$^{-1}$) | 2809.6 a | 3309.6 a | 3059.6 a | 2742.9 b | 3312.9 a | 3027.9 a |
| $D_3$ (8 plants driper$^{-1}$) | 2679.3 b | 3326.1 a | 3002.7 a | 2709.4 b | 3362.6 a | 3036.0 a |
| $D_4$ (10 plants driper$^{-1}$) | 1468.6 c | 1668.6 c | 1568.6 c | 1551.9 c | 1951.9 c | 1751.9 c |
| D5 (12 plants driper$^{-1}$) | 1051.9 d | 1351.9 c | 1201.9 d | 1185.2 c | 1518.6 c | 1351.9 d |
| Mean | 2197.1 b | 2474.6 a | | 2247.1 b | 2559.9 a | |
| | | | **Leaf area index** | | | |
| $D_1$ (4 plants driper$^{-1}$) | 2.83 c | 2.59 d | 2.71 d | 2.90 c | 2.53 c | 2.71 c |
| $D_2$ (6 plants driper$^{-1}$) | 4.01 b | 4.73 b | 4.37 b | 3.92 b | 4.73 b | 4.33 b |
| $D_3$ (8 plants driper$^{-1}$) | 5.10 a | 6.34 a | 5.72 a | 5.16 a | 6.41 a | 5.78 a |
| $D_4$ (10 plants driper$^{-1}$) | 3.50 bc | 3.97 c | 3.73 c | 3.69 b | 4.65 b | 4.17 b |
| D5 (12 plants driper$^{-1}$) | 3.01 c | 3.86 c | 3.43 c | 3.39 b | 4.34 b | 3.86 b |
| Mean | 3.69 b | 4.30 a | | 3.81 b | 4.53 a | |

In a column, means with different letter denoted statistically difference between treatment groups according to Duncan's test ($P < 0.05$).

There were significant variations between the two varieties with respect to all vegetative growth parameters at two sampling times, with the exception of plant height (Tables 2 and 3). The Giza716 variety showed the highest number of branches per plant. The total dry weight per plant, leaf area per plant and leaf area index for Giza 843 were higher than those of Giza 716 by approximately 12.7, 7.6 and 11.7% at 70 days after sowing and 12.7, 11.7 and 15.0% at 100 days after sowing, respectively, as averaged over the two seasons (Tables 2 and 3). Although, plant density had no significant effect on the number of branches per plant for Giza 843, its average was reduced over two seasons for Giza 716 by 40.0 and 55.7% at 70 days after sowing and 45.1 and 60.2% at 100 days after sowing at 10 and 12 plants dripper$^{-1}$, respectively, when compared to the low plant density. For Giza 716, the total dry weight and leaf area per plant were significantly decreased with the increase in plant densities. For Giza 843, these parameters gradually increased with increasing plant density up to 8 plants dripper$^{-1}$ and significantly decreased at densities of 10 and 12 plants dripper$^{-1}$; this result was observed in both growing seasons and at both sampling times. The highest and lowest LAI values for both varieties were obtained at 8 and 4 plants dripper$^{-1}$, respectively (Tables 2 and 3).

### *Effect of plant density, variety and their interaction on yield and yield components*

While, all yield components (i.e., number of pods and seeds per main stem and branches, weight of pods per main stem and branches, total number of pods and seeds per plant and total weight of pods per plant) gradually decreased with increasing plant density, the seed yield per hectare was significantly increased with densities up to8 plants dripper$^{-1}$ and thereafter slightly decreased at 10 plants dripper$^{-1}$ with no significant differences observed between 4 and 12 plants dripper$^{-1}$ (Tables 4 and 5). For instance, as averaged over the two seasons, as plant density was increased from 4 plants dripper$^{-1}$ to 6, 8, 10 and 12 plants dripper$^{-1}$, all evaluated yield components were reduced by an average of 14.9, 34.6, 54.4 and 78.4%, respectively (Tables 4 and 5). However, compared with4 plants dripper$^{-1}$, the seed yield per hectare at 6, 8 and 10 and 12 plants dripper$^{-1}$ was significantly increased by 39.4, 42.3, 33.7 and 14.4% in 2011 and by 29.4, 33.9, 28.6 and 14.5% in 2012, respectively (Table 5).

**Table 4.** Effects of varieties, plant population density and their combination on selected yield components in 2011 and 2012.

| | 2011 | | | 2012 | | |
|---|---|---|---|---|---|---|
| | **Giza 716 (V1)** | **Giza 843 (V2)** | **Mean** | **Giza 716 (V1)** | **Giza 843 (V2)** | **Mean** |
| | | | **Number of pods per main stem** | | | |
| $D_1$ (4 plants driper$^{-1}$) | 10.3 a | 18.1 a | 14.2 a | 14.3 a | 19.9 a | 17.1 a |
| $D_2$ (6 plants driper$^{-1}$) | 9.0 ab | 16.4 a | 12.7 b | 11.7 b | 18.2 a | 15.0 b |
| $D_3$ (8 plants driper$^{-1}$) | 7.1 bc | 13.0 b | 10.1 c | 10.7 b | 15.0 b | 12.9 b |
| $D_4$ (10 plants driper$^{-1}$) | 6.2 c | 10.2 c | 8.2 d | 8.0 c | 11.2 c | 9.6 c |
| D5 (12 plants driper$^{-1}$) | 3.1 d | 4.5 d | 3.8 e | 3.3 d | 4.2 d | 3.8 d |
| Mean | 7.2 b | 12.5 a | | 9.6 b | 13.7 a | |
| | | | **Number of pods per branches** | | | |
| $D_1$ (4 plants driper$^{-1}$) | 12.4 a | 6.3 a | **9.3 a** | 12.4 a | 6.6 a | 9.5 a |
| $D_2$ (6 plants driper$^{-1}$) | 8.6 b | 6.5 a | **7.5 b** | 9.3 b | 6.1 a | 7.7 b |
| $D_3$ (8 plants driper$^{-1}$) | 6.3 c | 4.5 b | **5.4 c** | 5.6 c | 3.4 b | 4.5 c |
| $D_4$ (10 plants driper$^{-1}$) | 4.4 d | 2.7 c | **3.5 d** | 4.7 d | 2.2 b | 3.5 d |
| D5 (12 plants driper$^{-1}$) | 3.1 e | 2.3 c | **2.7 d** | 2.3 e | 2.6 b | 2.4 e |
| Mean | 7.0 a | 4.5 b | | 6.9 a | 4.2 b | |
| | | | **Number of seeds per main stem** | | | |
| $D_1$ (4 plants driper$^{-1}$) | 27.1 a | 40.3 a | **33.7 a** | 27.5 a | 44.3 a | 35.9 a |
| $D_2$ (6 plants driper$^{-1}$) | 27.8 a | 38.0 a | **32.9 a** | 29.2 a | 38.7 a | 34.0 a |
| $D_3$ (8 plants driper$^{-1}$) | 18.8 b | 28.7 b | **23.7 b** | 20.0 b | 27.0 b | 23.5 b |
| $D_4$ (10 plants driper$^{-1}$) | 13.6 c | 18.7 c | **16.2 c** | 14.6 c | 18.7 c | 16.7 c |
| D5 (12 plants driper$^{-1}$) | 5.2 d | 8.4 d | **6.8 d** | 6.6 d | 8.9 d | 7.7 d |
| Mean | 18.5 b | 26.8 a | | 19.6 b | 27.5 a | |
| | | | **Number of seeds per branches** | | | |
| $D_1$ (4 plants driper$^{-1}$) | 26.8 a | 23.8 a | **25.3 a** | 32.5 a | 26.7 a | 29.6 a |
| $D_2$ (6 plants driper$^{-1}$) | 20.2 b | 16.2 b | **18.2 b** | 24.2 b | 19.1 b | 21.7 b |
| $D_3$ (8 plants driper$^{-1}$) | 17.2 b | 14.4 b | **15.8 c** | 21.4 b | 16.7 b | 19.0 c |
| $D_4$ (10 plants driper$^{-1}$) | 6.9 c | 4.8 c | **5.8 d** | 8.0 c | 6.5 c | 7.2 d |
| D5 (12 plants driper$^{-1}$) | 4.1 c | 3.2 c | **3.7 e** | 3.8 d | 3.9 c | 3.8 e |
| Mean | 15.0 a | 12.5 b | | 18.0 a | 14.6 b | |
| | | | **Weight of pods per main stem (g)** | | | |
| $D_1$ (4 plants driper$^{-1}$) | 30.0 a | 39.3 a | **34.7 a** | 31.7 a | 41.0 a | 36.3 a |
| $D_2$ (6 plants driper$^{-1}$) | 26.3 b | 33.3 b | **29.8 b** | 29.7 a | 35.0 b | 32.3 b |
| $D_3$ (8 plants driper$^{-1}$) | 20.7 c | 27.7 c | **24.2 c** | 23.3 b | 30.0 c | 26.7 c |
| $D_4$ (10 plants driper$^{-1}$) | 18.7 c | 25.7 c | **22.2 c** | 20.7 b | 26.9 c | 23.8 d |
| D5 (12 plants driper$^{-1}$) | 8.7 d | 8.7 d | **8.7 d** | 10.0 c | 9.3 d | 9.7 e |
| Mean | 20.9 a | 26.9 a | | 23.1 b | 28.4 a | |

In a column, means with different letter denoted statistically difference between treatment groups according to Duncan's test ($P < 0.05$).

There were significant differences between the two varieties in yield and yield components. The Giza 843 variety produced higher yield components for the main stem than Giza 716, whereas the latter variety had higher yield components for branches than Giza 843 (Tables 4 and 5). For instance, as averaged over the two seasons, the number of pods and seeds per main stem as well as the pod weight per main stem for Giza 843 were 36.2, 29.9 and 20.5% higher, respectively, than those for Giza 716. The number of pods and seeds per branch as well as the weight of pods per branch for Giza 716was 37.4, 17.7 and 20.3% higher, respectively, than those for Giza 843 (Tables 4 and 5).

In addition, the response of the yield and yield components of the two varieties were influenced by plant density. For Giza 843, the highest seed yield was obtained at 8 or 10 plants dripper$^{-1}$; however, for Giza 716, the highest seed yield was obtained at 6 or 8 plants dripper$^{-1}$. The seed yield of Giza 716 at 10 plants dripper$^{-1}$ was occasionally comparable to those at 4 plants dripper$^{-1}$, but for Giza 843, it was not (Table 5). At low plant density (4 plants dripper$^{-1}$), Giza 716 had seed yield values that were 30.6 and 24.1% higher than those of Giza 843; however, the latter had seed yield values that were 13.9 and 9.01% higher than those of Giza 716 at higher plant density (12 plants dripper$^{-1}$) in 2011 and 2012, respectively (Table 5).

**Table 5** Effects of varieties, plant population density and their combination on selected yield components and seed yield in 2011 and 2012.

| | 2011 | | | 2012 | | |
|---|---|---|---|---|---|---|
| | **Giza 716 (V1)** | **Giza 843 (V2)** | **Mean** | **Giza 716 (V1)** | **Giza 843 (V2)** | **Mean** |
| **Weight of pods per branches (g)** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 21.0 a | 17.3 a | 19.2 a | 19.7 a | 17.3 a | 18.5 a |
| $D_2$ (6 plants driper$^{-1}$) | 18.3 a | 15.0 a | 16.7 b | 17.3 a | 16.3 a | 16.8 b |
| $D_3$ (8 plants driper$^{-1}$) | 12.7 b | 10.0 b | 11.3 c | 12.3 b | 10.7 b | 11.5 c |
| $D_4$ (10 plants driper$^{-1}$) | 8.7 c | 5.0 c | 6.8 d | 9.7 c | 5.7 c | 7.7 d |
| D5 (12 plants driper$^{-1}$) | 4.0 d | 1.7 d | 2.8 e | 4.0 d | 2.7 d | 3.3 e |
| Mean | 12.9 a | 9.8 b | | 12.6 a | 10.5 b | |
| **Total number of pods per plant** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 22.7 a | 24.4 a | 23.6 a | 26.7 a | 26.5 a | 26.6 a |
| $D_2$ (6 plants driper$^{-1}$) | 17.6 b | 22.9 a | 20.3 b | 20.9 b | 24.3 a | 22.7 b |
| $D_3$ (8 plants driper$^{-1}$) | 13.5 c | 17.5 b | 15.5 c | 16.4 c | 18.4 b | 17.4 c |
| $D_4$ (10 plants driper$^{-1}$) | 10.6 d | 12.9 c | 11.8 d | 12.7 d | 13.4 c | 13.1 d |
| D5 (12 plants driper$^{-1}$) | 6.3 e | 6.9 d | 6.6 e | 5.6 e | 6.8 d | 6.2 e |
| Mean | 14.1 b | 16.9 a | | 16.5 a | 17.9 a | |
| **Total number of seeds per plant** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 53.9 a | 64.1 a | 59.0 a | 59.9 a | 71.0 a | 65.5 a |
| $D_2$ (6 plants driper$^{-1}$) | 48.0 b | 54.2 b | 51.1 b | 53.3 b | 57.9 b | 55.6 b |
| $D_3$ (8 plants driper$^{-1}$) | 36.0 c | 43.0 c | 39.5 c | 41.4 c | 43.7 c | 42.5 c |
| $D_4$ (10 plants driper$^{-1}$) | 20.5 d | 23.4 d | 22.0 d | 22.6 d | 25.1 d | 23.9 d |
| D5 (12 plants driper$^{-1}$) | 9.3 e | 11.6 e | 10.5 e | 10.4 e | 12.7 e | 11.6 e |
| Mean | 33.5 b | 39.3 a | | 37.5 b | 42.1 a | |
| **Total weight of pods per plant (g)** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 51.0 a | 56.7 a | **53.8 a** | 51.3 a | 58.3 a | 54.8 a |
| $D_2$ (6 plants driper$^{-1}$) | 44.7 b | 48.3 b | **46.5 b** | 47.0 b | 51.3 b | 49.1 b |
| $D_3$ (8 plants driper$^{-1}$) | 33.3 c | 37.7 c | **35.5 c** | 35.7 c | 40.7 c | 38.2 c |
| $D_4$ (10 plants driper$^{-1}$) | 27.3 d | 30.7 d | **29.0 d** | 30.3 d | 32.5 d | 31.4 d |
| D5 (12 plants driper$^{-1}$) | 12.7 e | 10.3 e | **11.5 e** | 14.0 e | 12.0 e | 13.0 e |
| Mean | 33.8 a | 36.7 a | | 35.7 a | 39.0 a | |
| **Seed yield (kg ha-1)** | | | | | | |
| $D_1$ (4 plants driper$^{-1}$) | 1983.2 bc | 1375.6 d | 1679.4 c | 2516.6 bc | 1908.9 d | 2212.7 c |
| $D_2$ (6 plants driper$^{-1}$) | 2829.8 a | 2719.8 b | 2774.8 b | 3113.2 a | 3153.2 b | 3133.2 b |
| $D_3$ (8 plants driper$^{-1}$) | 2632.4 a | 3193.2 a | 2912.8 a | 3085.7 a | 3609.9 a | 3347.8 a |
| $D_4$ (10 plants driper$^{-1}$) | 2167.4 b | 2898.1ab | 2532.7 b | 2564.8 b | 3634.0 a | 3099.4 b |
| D5 (12 plants driper$^{-1}$) | 1815.7 c | 2109.9 c | 1962.8 c | 2465.7 c | 2709.9 c | 2587.8 c |
| Mean | 2285.7 b | 2459.3 a | | 2749.2 b | 3003.2 a | |

In a column, means with different letter denoted statistically difference between treatment groups according to Duncan's test ($P < 0.05$).

*Production functions*

Production functions of number of plants per dripper versus crop growth parameters, vegetative growth parameters at 70 and 100 days after sowing, yield components and seed yield in both growing seasons are shown in Figs 2 and 3. When the production functions were done according to the crop growth parameters (RGR, NAR and LAD), vegetative growth parameters (total dry weight and leaf area per plant and leaf area index at 70 and 100 days after sowing) and seed yield ha$^{-1}$, the number of plants per dripper versus these parameters exhibited strong quadratic relationships with the exception of the total dry weight at 70 days after sowing, which instead showed a linear relationship (Figs. 2 and 3). However, the production functions of yield components (total number of pods and seeds per plant and total weight of pods per plant) versus the number of plants per dripper exhibited strong linear relationships (Fig. 3).

*Correlations between seed yield and related traits*

Averaged over two seasons, simple correlation coefficients between seed yield and its related traits are shown in Table 6. Seed yield correlated positively with crop growth parameters and vegetative growth parameters but showed no correlation with any of the yield components (Table 6).

## DISCUSSION

In plant densities studies, intra- and inter-plant competition are two of the most important stresses affecting biomass production, crop yield and economic profitability. Increasing plant density per unit area increases both types of competition for production inputs such as solar radiation, water and nutrients. Low densities lead to inefficient use of these inputs. In this study, there was only one competition (intra-plant competition) whereas inter-plant competition was not a factor because there was sufficient distance between laterals in the drip design (1.4 m apart laterals). Intra-plant competition in this study arises from the distribution pattern of the plants around the drippers, which allowed different plant spacing of 15.0, 10.0, 7.5, 6.0 and 5.0 cm for treatments of densities 4, 6, 8,10 and 12 plants dripper$^{-1}$, respectively (Fig. 1). Notably, in this study, the widest inter-plant spacing combined with the narrowest intra-plant spacing (1.4 m × 0.05 m) gave the maximum plant density of only 28.6 plant m$^{-2}$. According to the literature, plant density under conventional cultural practices can range from 10 to 100 plants m$^{-2}$ (López-Bellido et al., 2005; Mathews et al., 2008; Khalil et al, 2010; Ragab et al., 2010; Bakry et al., 2011). This finding raises the question of whether the plant densities in this study allowed for the potential maximum seed yield even with such great differences in densities compared to conventional cultural practices. Therefore, this study was conducted to understand the behaviour of growth and to better calculate the economic production function of two varieties of faba bean differing in branch capacity when grown in drip systems with only one competition parameter by increasing the space between laterals.

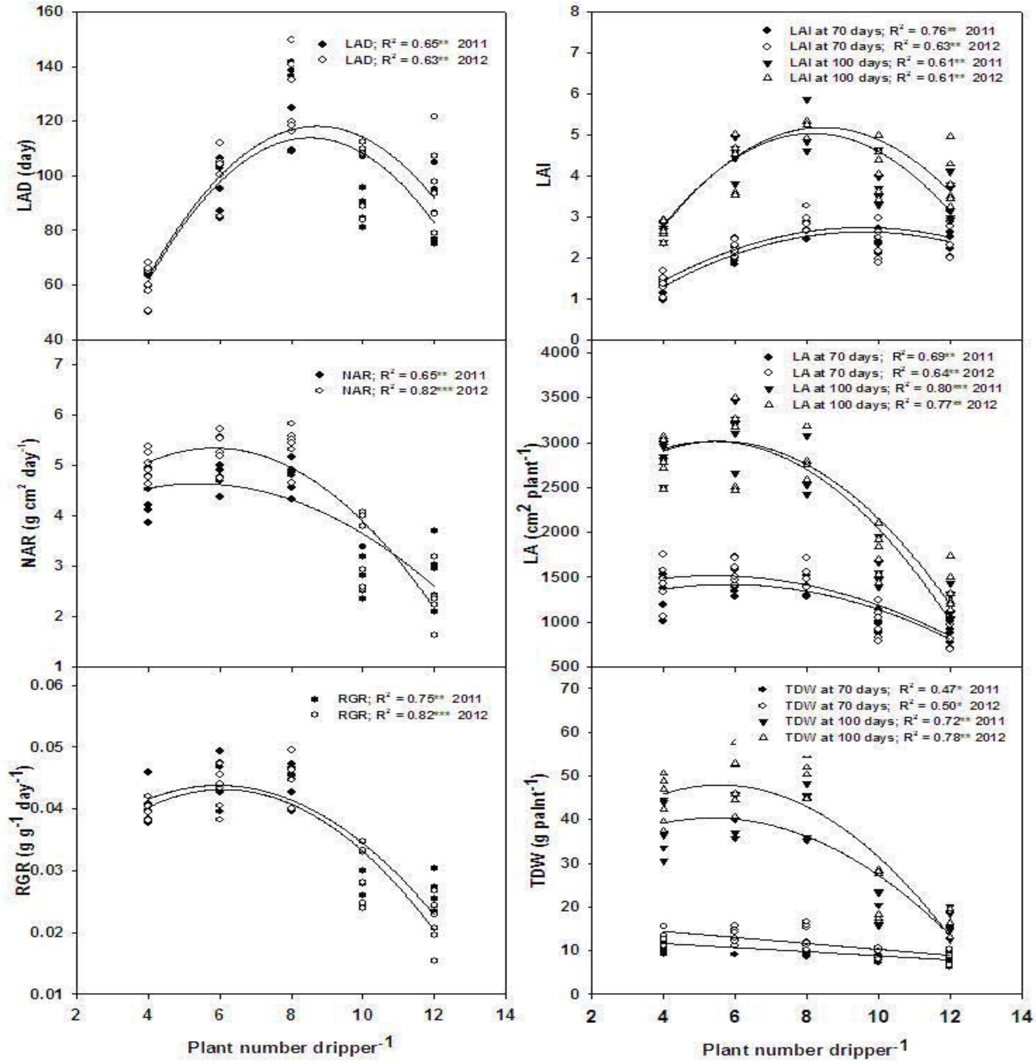


**Fig. 2.** Relationship between number of plants per dripper and crop growth parameters (relative growth rate, RGR; net assimilation rate, NAR and leaf area duration, LAD) and vegetative growth parameters at 70 and 100 days after sowing (total dry weight per plant, TDW; leaf area per plant, LA and leaf area index, LAI) in 2011 and 2012. Regression equations; *, ** and ***indicate significant at 0.05, 0.01 and 0.001P level, respectively.

**Table 6.** Simple correlation coefficients (lower right) and their significance levels (upper left) between seed yield and its related traits (data averaged over two seasons)

| | Seed yield (kg ha-1) |
|---|---|
| **Crop growth parameters** | |
| RGR (g g-1 day-1) | 0.53** |
| NAR (g cm-2 day-1) | 0.51** |
| LAD (day) | 0.70*** |
| **Vegetative growth parameters** | |
| Total dry weight at 70 days after sowing (g plant$^{-1}$) | 0.46** |
| Total dry weight at 100 days after sowing (g plant$^{-1}$) | 0.52** |
| Leaf area per plant at 70 days after sowing (cm$^2$) | 0.53** |
| Leaf area per plant at 100 days after sowing (cm$^2$) | 0.50** |
| Leaf area index 70 days after sowing | 0.49** |
| Leaf area index 100 days after sowing | 0.76*** |
| **Yield components** | |
| Number of pods per main stem | 0.26 ns |
| Number of pods per branches | 0.01 ns |
| Number of seeds per main stem | 0.22 ns |
| Number of seeds per branches | 0.07 ns |
| Weight of pods per main stem (g) | 0.30 ns |
| Weight of pods per branches (g) | 0.10 ns |
| Total number of pods per plant | 0.19 ns |
| Total number of seeds per plant | 0.17 ns |
| Total weight of pods per plant (g) | 0.24 ns |

*: significant at P < 0.01; **: Significant at P < 0.001; ns: non-significant.

Crop growth parameters such as RGR, NAR and LAD provide a framework for identifying potentially useful traits for yield improvement and to help us to understand the physiological response of growth and yield to plant density stress (Ball et al., 2001). These crop parameters reflect canopy development and efficiency of solar radiation interception, thereby reflecting the efficiency of photosynthesis and the final yield (Muchow et al. 1986). Furthermore, RGR is used as comprehensive trait for integrating morphological and physiological characteristics (McGraw and Garbutt, 1990). In this study, the highest RGR, NAR and LAD values were obtained at medium plant density (6 or 8 plants dripper$^{-1}$), while the highest plant density (10 or 12 plants dripper$^{-1}$) resulted in significantly lower values for RGR and NAR and higher values for LAD. However, the low plant density (4 plants dripper$^{-1}$) exerted moderate effects on RGR and NAR but produced the lowest values for LAD (Table 1). Increased crop growth parameters at medium densities (6 or 8 plants dripper$^{-1}$) may be because both densities exhibited the highest values for total dry weight and LAI, especially at 100 days after sowing, which corresponds to the start of flowering and the start of pod filling stages (Tables 2 and 3). This finding is consistent with the results of López-Bellido et al. (2005) for faba bean, who reported that the behaviour of crop growth indices in response to variation in plant density is generally linked to the dry matter and LAI values attained over various crop stages. However, the very narrowest intra-plant spacing (10 or 12 plant dripper$^{-1}$) accelerated leaf senescence and increased competition for light due to excessive shading between leaves. Whereas plants grown at very wide intra-plant spacing (4 plants dripper$^{-1}$) intercepted less light per plant during much of their life cycle than those grown at optimal plant density (Poulain et al., 1986; Polignand and Uggenti, 1989; Amato et al., 1992). The optimum plant density treatment that maintains adequate plant-to-plant spacing produces a complete canopy that is capable of maximising light interception. Therefore, a quadratic relationship has been found between the three crop growth parameters and plant density for the development of production functions (Fig. 2). The optimum plant density computed from the quadratic functions was approximately 6 plants dripper$^{-1}$ for RGR and NAR and approximately 9 plants dripper$^{-1}$ for LAD. These results are in partial agreement with those of El-Zahab et al. (1981), who observed an increase in RGR and NAR values at moderate densities, and Pilbeam et al. (1991) who reported that LAD is greater at higher plant densities during the vegetative stage.

Pilbeam et al. (1991) reported that until flowering in faba bean, the highest LAI values are achieved at the highest densities; however, the opposite holds true during pod development (i.e., the final LAI was greatest at lower densities). In this study, at 70 days after sowing, the highest LAI values were obtained at densities of 8 plants dripper$^{-1}$ followed by densities of 10 and 12 plants dripper$^{-1}$. However, at 100 days after sowing, a density of 8 plants dripper$^{-1}$ still produced the highest LAI values followed by a density of 6 plants dripper$^{-1}$, while a density of 4 plants dripper$^{-1}$ produced the lowest LAI values at both sampling times (Tables 2 and 3). Therefore, the optimum plant density that was computed from the quadratic functions of the relationship between LAI and plant density was approximately 10 plants dripper$^{-1}$ at 70 days after sowing and approximately 8 plants dripper$^{-1}$ at 100 days after sowing (Fig. 2). This finding indicates that during the early stages of vegetative growth, high plant densities will prompt higher LAI and apparently delay competition between plants. However, at later stages, high plant densities lead to rapid leaf senescence and competition between plants, which lead to decreases in LAI and dry matter accumulation. Therefore, the higher plant density (10 or 12 plants dripper$^{-1}$) resulted in a greater decrease in total dry weight and leaf area per plant measured at 100 days than at 70 days after sowing (Tables 2 and 3). In addition, the relationship between plant density and total dry weight or leaf area per plant at 100 days were higher than at 70 days after sowing (Fig. 2).

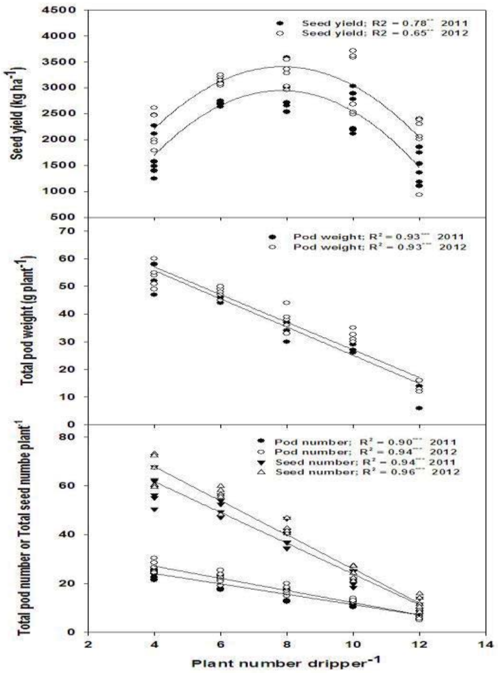


**Fig. 3.** Relationship between number of plants per dripper and total number of pods and seeds per plant, weight of pods per plant and seed yield per hectare in 2011 and 2012. Regression equations; ** and ***indicate significant at 0.01 and 0.001Plevel, respectively

In this study, increasing plant density resulted in a significant decrease in all yield components of individual plants, while seed yield increased with densities up to 8 plants dripper$^{-1}$ and thereafter slightly decreased at 10 and 12 plants dripper$^{-1}$ (Tables 4 and 5). Furthermore, final seed yield per hectare was significantly positively correlated with the crop growth and vegetative growth parameters, but not with the yield components of individual plants (Table 6). This finding shows that the final seed yield of faba bean did not reflect the response of yield components to plant density but did reflect the response of vegetative and crop growth parameters to plant density. The study of Achakzai and Taran (2011) agrees closely with the results from our study. Taken together, these results indicate that growth dynamic factors that occurred during the vegetative growth period could help explain the necessary management required to achieve optimal yields. Moreover, an increased understanding of how growth dynamic factors regulates faba bean yield in response to plant density could help us to explain the sensitive relationship between plant density and canopy development. This information may be especially relevant when applying a new agronomic practice of growing faba bean under less favourable environmental conditions. Mellendorf (2011) reported that the relationships between plant density and yield are explained by two concepts. First, maximum crop yield can only be achieved if the crop community is able to produce sufficient leaf area to provide maximum light interception during reproductive growth. Second, equidistant plant spacing maximises yield because it minimises plant-to-plant competitions. Therefore, the reduction in yield caused by high plant density (12 plant dripper$^{-1}$) could be explained by the competition between plants for this treatment begins during early vegetative growth. This early competition increases shading between leaves, leading to insufficient carbon fixation, increases respiration rate and increases intra-plant competition between vegetative and reproductive structures for assimilates. However, the reduction in yield caused by low plant density (4 plants dripper$^{-1}$) could be explained by the canopy development at the early stages for this treatment being insufficient to maximise light interception. Therefore, if the planting density is too high, plants may compete against each other, and the performance of individual plants may become a limiting factor for maximum crop yield. However, when the planting density is too low, each individual plant may perform at its maximum capacity, but there may be insufficient total plants to reach the optimum yield. In this case, total yield of the crop becomes a limiting factor.

This study also indicated that the effect of plant density on growth and yield of faba bean varied independently of faba bean genotypes. For Giza 716, which had more branching per plant than Giza 843, increasing plant density resulted in a significant decrease in total dry weight and leaf area per plant. For Giza 843, the both parameters increased with densities up to 8 plants dripper$^{-1}$ and significantly decreased at densities of 10 and 12 plants dripper$^{-1}$ (Tables 2 and 3). Seed yield of Giza 716 increased with densities up to 8 plants dripper$^{-1}$ while for Giza 843, it increased with densities up to 10 plants dripper$^{-1}$ (Table 5). These results indicate that the contribution of branches to seed yield decreased with increasing plant density due to excessive competition. This could be advantageous for Giza 716 under low density because plants compensate for open space by producing more branches. However, under high plant density, the branches contribute less than the main stem to seed yield.

Because the cost of faba bean seeds increases each year, there is a greater need to define optimum plant density to maximise yields and economic return. In this study, the optimal seeding rates for two varieties are presented in Fig 4. This figure simulates the relative net yields at the five plant densities when the seed cost to product price ratio ranges from 0:1 to 3:1. For Giza 716 and Giza 843, all the cost to product price ratios examined indicated that net yield increases up to a seeding rate of 118.0 (6 plants dripper$^{-1}$) and 118.8 kg ha$^{-1}$ (8 plants dripper$^{-1}$), respectively. The relative net yields for Giza 716 at a 118.0 kg ha$^{-1}$ seeding rate with a 1:1 ratio were occasionally comparable to those at a 156.8 kg ha$^{-1}$ seeding rate with a 0:1 ratio. However, the relative net yields for Giza 843 at a 118.8 kg ha$^{-1}$ seeding rate with a 1:1 ratio were occasionally comparable to those at a 148.8 kg ha$^{-1}$ seeding rate with a 0:1 ratio. These results indicate that economically optimum-seeding rates could be 25% less than the optimum seeding rate due to increasing seed costs. Therefore, one might hypothesise that seeding rates below current practices could be used to lower seed costs without reducing net profit. This hypothesis is of increasing interest due to the increase in seed costs for faba bean producers.

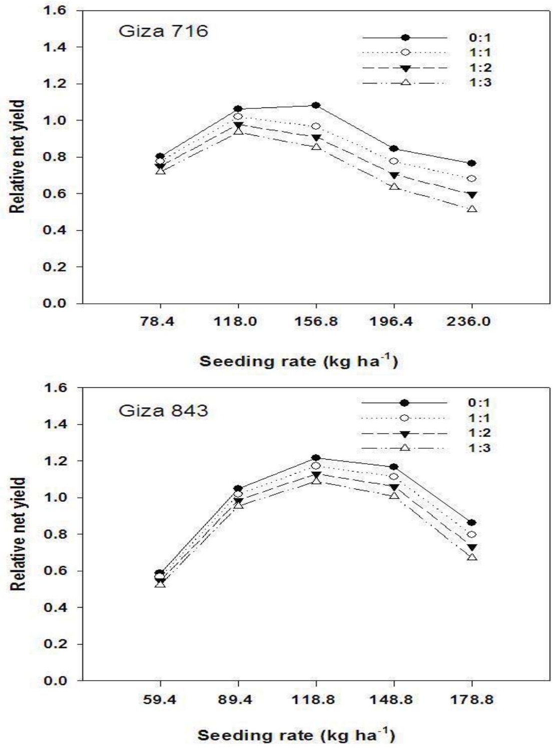


**Fig. 4.** Simulations of yield for Giza 716 and Giza 843 at five plant density when seed cost are nil, 1, 2 or 3 times of the product price which represent in the figure as 0:1, 1:1, 1:2 or 1:3, respectively.

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