Effect of different plant densities on growth, yield and nutritional quality of sesame (*Sesamum indicum*) in Morocco

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Abstract

A field experiment was carried out to assess the effect of plant density on growth, yield components and nutritional quality of *Sesamum indicum* in Taounate, Morocco. The experiment was a randomized block design using three levels of plant density: 100,104 plants ha^{-1}, 11,104 plants ha^{-1}, and 4,104 plants ha^{-1}. Results showed that plant density affected the majority of measured parameters. Low plant density (4,104 plants ha^{-1}) increased plant height (150 cm), number of capsules per plant (94.3), number of seeds per capsule (61.2) and capsules length (29.8 mm). On the other hand, seed yield, oil yield, and protein yield increased with increasing plant density. In conclusion, it is recommended to adjust the plant density to 100,104 plants per hectare under the conditions of Taounate, Morocco to achieve maximum yield with better nutritional quality.

Keywords: *Sesamum indicum*, Plant density, Growth, Yields, Nutritional quality

INTRODUCTION

Sesame (*Sesamum indicum* L.), belonging to the Pedaliaceae family, is a plant cultivated for its edible seeds. The economic value of these seeds is primarily related to their oil content, which can reach up to 49% (El Hanafi *et al*., 2019), with a high diversity of unsaturated fatty acids (85%) and saturated fatty acids (15%) (Teklu *et al*., 2022). Additionally, sesame is characterized by a significant protein content (20%) (El Hanafi *et al*., 2019), primarily consisting of globulin and albumin (Cui *et al*., 2021). *Sesamum indicum* exhibits notable biological activities, including antihypertensive potential (Wichitsranoi *et al*., 2011), antihyperglycemic effects (Ghoreishi *et al*., 2022), and a reduction in plasma cholesterol levels (Chen *et al*., 2005). It is considered a potent antioxidant, thanks to its high content of bioactive compounds such as sesamol, sesamolin, and sesamin (Sallam *et al*., 2022).

Currently, Africa has been the leading producer, accounting for 56.8% of sesame global production (FAOSTAT, 2024). In Morocco, the sesame sector consistently generates a substantial production value ranging from 15 to 25 million Dirhams annually. In the Tadla region, which represents over 90% of the national agricultural area sown to sesame, production ranged from 3.7 to 6.6 tons per year between 2018 and 2022.

The Moroccan government has adopted a national strategy called "Green Generation" to boost the agricultural sector and support farmers who still rely on traditional farming methods. Many studies have highlighted numerous opportunities to enhance plant productivity by use of appropriate crop management practices (Devkota, 2023). Plant density refers to the quantity of individual plants within a specific area of land (Haque, 2022). It has been shown that high plant population is one of the main factors that influence growth factors and cause competition among plants for resources (light, CO_2, etc..) which consequently affect plant productivity, as shown in canola (Momoh *et al*., 2001), soybean (Norsworthy *et al*., 2005), and sunflower (Ibrahim, 2012). Also, Lisson and Mendham (2000) observed that increasing plant density of flax from 390 to 530 plant/m² enhances performance. According to Turner (1991), the number of flax capsules per plant doubled as the population density increased from 400 to 900 plant/m². Based on Arslanoglu *et al*. (2022), the best values in terms of flax yield and seeds are recorded for 2000 plants/m², whereas 500 plants/m² show the lowest values. Choosing the right plant density is essential for maximizing yield potential (Haque, 2022). Keeping this in view, this study was conducted to optimize the plant density of Moroccan sesame under the agro-climatic conditions of Taounate.

MATERIAL AND METHODS

Experimental site

The experiment was conducted at the National Institute of Medicinal and Aromatic Plants between June and October 2015. Geographically, the experimental field is located in Morocco, at a latitude of 34.4992519 and a longitude of 4.8035079. The meteorological parameters of the experiment station are noted in Table 1.

Table 1: Climatic data of the experimental site

	June	July	August	September	October
C°min	15.9	18.5	18.5	15.5	11.5
C°max	29.8	34.0	34.0	22.5	23.0
C°	22.8	26.2	26.2	22.5	17.2

The physical and chemical properties of the experimental soil (0-30 cm depth) are determined in Table 2. Soil organic matter was quantified using the Walkley-Black method (Walkley and Black, 1934). After a strong acid attack, the concentrations of P, K were analyzed by coupled plasma atomic emission spectrometry (ICP-AES)

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(Zhao *et al.*, 1994). N was determined by the Kjeldhal distillation method (Khalid *et al.*, 2003). The experimental design was a randomized block design replicated three times, with three plant densities: 100.10^4 plants. ha^{-1}, 11.10^4 plants. ha^{-1}, and 4.10^4 plants. ha^{-1}.

Table 2: Chemical and physical parameters of soil

Physicals proprieties		Chemical proprieties	
Clay %	14	PH	7.87
Fine Silt %	37	OM%	1.01
Coarse Silt %	12	N (mg/kg)	0.01
Fine sand%	22	P(mg/kg)	5.40
Coarse sand %	15	K (mg/kg)	189

Sesame seeds were sown at a depth of 3-4 cm. No chemical or organic treatments were used. Different standard management practices such as weeding, gap filling, and irrigation were done as needed. Plots were harvested in October 2015, when the colour of the leaves changed from green to yellow. Mature plants were stacked vertically and allowed to dry under the sun.

Data Collection

To characterize the crop response of the studied plant according to the different plant density levels, we determined three types of parameters: growth, yield, and seed quality.

Growth parameters

***Plant height*:** At maturity plant height was measured from the base to the tip and was averaged in (cm).

Number of capsules per plant: number capsules of ten sample plants of each unit plot were counted.

Number of seeds capsule: From each sample plant, all the seeds of ten capsules were counted

***Thousand seed weight (g)*:** One thousand seeds from each plot were counted and weighed

Root development: root dry weight (g) and dry root length were determined.

Length of capsule (mm)

Yield parameters

Seed yield and biological yield were calculated, then the harvest index was determined using the following formula:

Harvest index (%) = seed yield (kg. ha^{-1}) / biological yield (kg. ha^{-1})

Biochemical parameters

Seed oil content (%) was determined by extracting sesame seeds with a soxhlet. The oil was recovered by evaporating the solvent using a rotary vacuum evaporator. Seed protein content (%) of the ground seed sample was determined according to a Kjeldhal distillation method as described by Khalid *et al.*, (2003), and then N% was multiplied by 6.25 to obtain protein content in sesame seeds (McKenzie *et al.*, 1954). Oil and protein yield (kg ha^{-1}) was estimated by multiplying the percentage of oil and protein by the seed yield per hectare. To determine nutrient content, grain samples were taken up with dilute HCL (Zhao *et al.*, 1994). Then, the nutrients were analysed by ICP-AES.

Statistical analysis

Statistical analysis was performed using SPSS. Data were subjected to one-way analysis of variance (ANOVA) in order to determine significant differences among the treatments. The results were considered significant at a $p < 0.05$. The correlation test with a significance level ($p < 0.05$ or $p < 0.01$) was based on the Pearson correlation coefficient.

RESULTS

Growth parameters

Plant height: The obtained results showed that plant density significantly affected the plants' length (Figure 1). The highest value (150 cm) was recorded in 100.10^4 plants. ha^{-1}, followed by 11.10^4 plants.ha^{-1} and 4.10^4 plants. ha^{-1}. Plant density significantly influenced plant height ($F = 29,6$; $P \leq 0.001$).

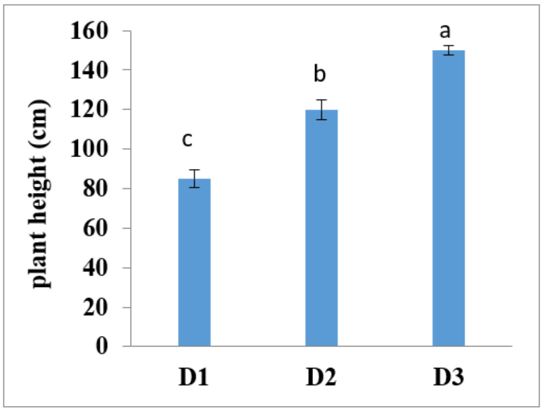

Figure 1: The effect of plant density on plant height

D1: 4.10^4 plants. ha^{-1}, D2: 11.10^4 plants. ha^{-1}, D3: 100.10^4 plants. ha^{-1}. Data labelled with different letters are significantly different at $P < 0.05$

Root development: The results showed that plant density had significantly affected the root dry weight (g) of sesame (p < 0, 05) (Figure 2). The highest dry root weight (3.39 ± 0.03 g) was obtained from 4.10^4 plants. ha^{-1}, followed by 11.10^4 plants. ha^{-1} with 2.89 g, and the lowest result (1.96 ± 0.06 g) was recorded from 100.10^4 plants. ha^{-1} (Figure 2A). Results also revealed that dry root length decreased with the increment of plant density (Figure 2B). Maximum root length (13.9 ± 1.18 cm) was produced at the highest density of 100.10^4 plants. ha^{-1}, and minimum root length 10.0 ± 0.85 cm was recorded in the lowest one (4.10^4 plants. ha^{-1}).

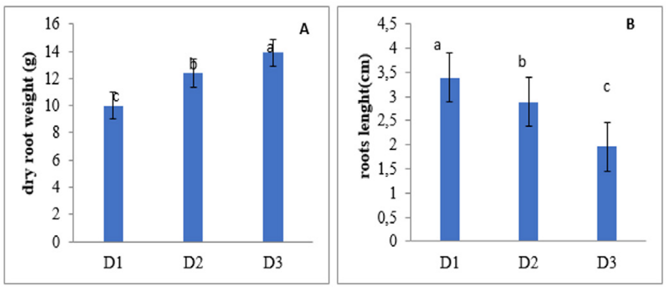

Figure 2: effect of plant density on the root dry weight (g) (A), root length (cm) (B)

D1: 4.10^4 plants. ha^{-1}, D2: 11.10^4 plants. ha^{-1}, D3: 100.10^4 plants. ha^{-1}. Data labelled with different letters are significantly different at $P < 0.05$

Capsules: The measured quantitative parameters for the capsules are shown in Figure 3. The more the plant density decreases, the higher the obtained values. This is statistically significant (F = 77. 7, P = 0.001), (F = 11.0, P ≤ 0.001) and (F = 17.6, P ≤ 0.001) respectively for the number of capsules per plant (Figure 3A), the number of seeds per capsule (Figure 3B), and the capsules length (Figure 3C).

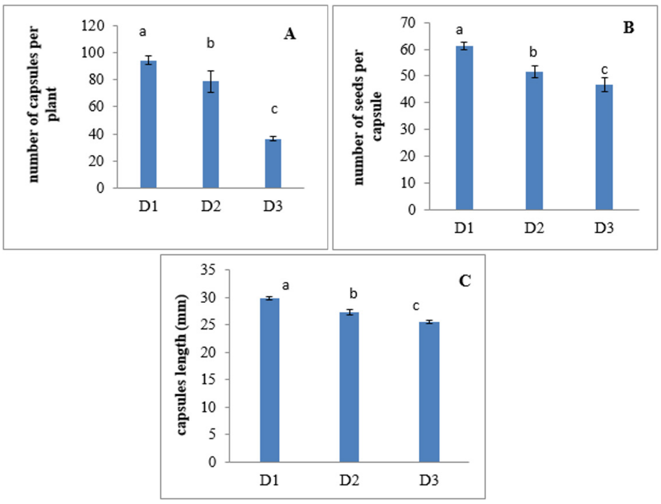

Figure 3: Effect of plant density on the number of capsules per plant (A), the number of seeds per capsule (B) and the capsules length (C)

D1: 4.10⁴ plants. ha⁻¹, D2: 11.10⁴ plants. ha⁻¹, D3: 100.10⁴ plants. ha⁻¹. Data labelled with different letters are significantly different at P < 0.05

1000 Seeds weight: 1000 seeds weight was significantly greater at 4.10⁴ plants. ha⁻¹ with 3.14 ± 0.06 g than 11.10⁴ plants. ha⁻¹ and 100.10⁴ plants. ha⁻¹ that produced respectively 2.96 ± 0.08 g and 2.83 ± 0.03 g (Figure 4).

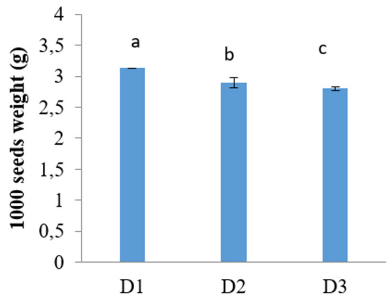

Figure 4: Effect of plant density on 1000 seeds weight (g)

D1: 4.10⁴ plants. ha⁻¹, D2: 11.10⁴ plants. ha⁻¹, D3: 100.10⁴ plants. ha⁻¹. Data labelled with different letters are significantly different at P < 0.05

Yields parameters

Seed yield: The population density remarkably affected seed yield (Figure 5A). Maximum yield was recorded at the highest density, 100.10⁴ plants. ha⁻ with 658 ± 10.5 kg/ha, while the minimum yield was recorded at the lowest one, 4.10⁴ plants.ha⁻¹ with 475 ± 10.4 kg/ha. These values are significantly different (F = 6.93, P <0.01).

Biological yield: The results showed that sowing of sesame at the plant density of 100.10⁴ plants.ha⁻¹ produced the maximum biological yield (2470 ± 29.8 kg ha⁻¹) compared with the one of 11.10⁴ plants.ha⁻¹ and 4.10⁴ plants.ha⁻¹ with 2372 ± 30.1 kg ha⁻¹ and 2169 ± 19.9 kg. ha⁻¹ respectively (Figure 5B). These differences are statistically significant (F = 13.1, P < 0.01).

Harvest Index: Increased plant density increased harvest index (Figure 5C). The highest index value (26.6 %) was recorded at 100.10⁴ plants.ha⁻¹ followed by 23.6% at 11.10⁴ plants.ha⁻¹, and 21.9% at 4.10⁴ plants.ha⁻¹.

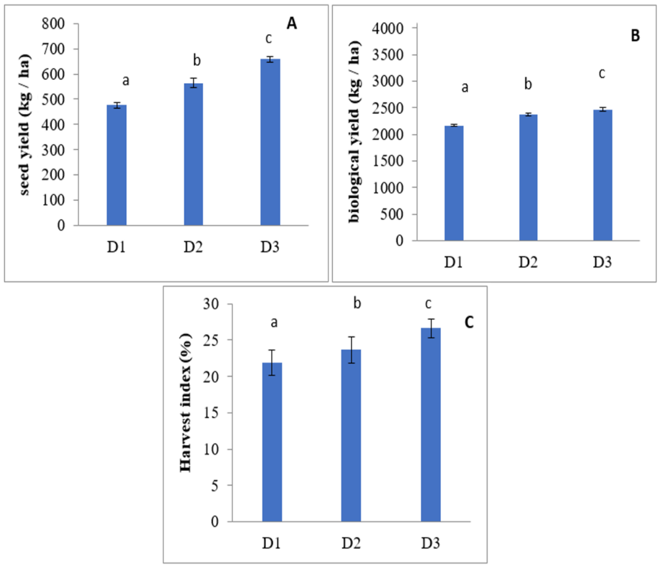

Figure 5: Effect of plant density on seed yield (kg. ha -1) (A), harvest index% (B), biological yield (kg. ha ⁻¹) (C)

D1: 4.10⁴ plants. ha⁻¹, D2: 11.10⁴ plants. ha⁻¹ plants ha⁻¹, D3: 100.10⁴ plants. ha⁻¹. Data labelled with different letters are significantly different at P < 0.05

Nutritional quality

Oil content: Increased plant density reduced seed oil content (Figure 6A). The seed oil content is more important at the lowest density (4.10⁴ plants.ha⁻¹) with a value of 52.9%, followed by 11.10⁴ plants.ha⁻¹ with 51.6%, and finally, the highest density of 100.10⁴ plants.ha⁻¹ with 51.3%. The statistical analysis revealed a significant difference between the mean yield values recorded at different planting densities (F = 4.8, P ≤ 0.05).

Seed oil yield: The highest oil yield per hectare (338 ± 3.65 kg.ha⁻¹ was achieved at the plant density 100.10⁴ plants.ha⁻¹, followed by 11.10⁴ plants.ha⁻¹, and 4.10⁴ plants.ha⁻¹ with 289 ± 11.2 kg.ha⁻¹ and 217 ± 5.3 kg.ha⁻¹ respectively (Figure 6B). The statistical analysis shows that plantation density had a significant effect on the oil yield (F=15.6, P <0,05).

Seed protein content: A slight variation in the percentage of proteins is observed in plants grown at different plant densities (Figure 6C), but this variation was not significant (F = 1.9, p> 0.05).

Protein yield: As shown in Figure 6D, plant density has a significant effect on protein yield per hectare, densities of 100.10⁴ plants.ha⁻¹, 11.10⁴ plants ha⁻¹ and 4.10⁴ plants.ha⁻¹ produced 135 ± 4.0 kg.ha⁻¹; 121 ± 3.7 kg.ha⁻¹ and 103 ± 3.6 kg.ha⁻¹ respectively. These differences are statistically significant (F = 14.4, p < 0.05).

Mineral content: Statistical analysis of data in this study showed that plant density affects the uptake of all nutrients under our conditions of crop growth (Table 3). Higher values of grain phosphorus, potassium, calcium, magnesium, and zinc (respectively 1532, 822, 1287, 283, 15.2 mg /100 g) were found with 4.10⁴ plants. ha⁻¹ which was statistically similar with 11.10⁴ plants. ha⁻¹.

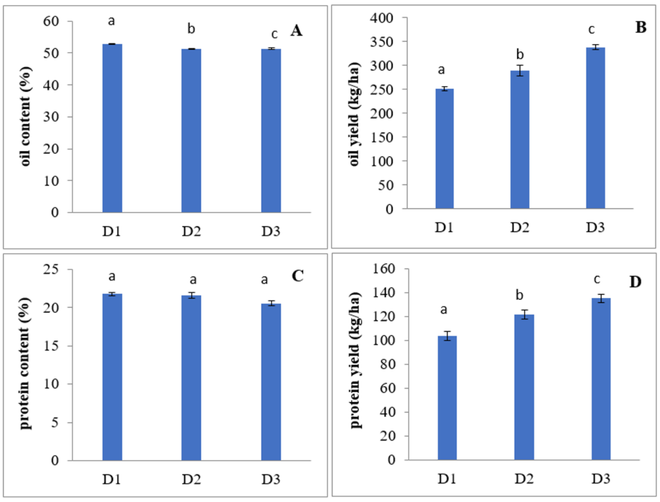

Figure 6: effect of plant density on Oil content% (A), yield oil (B), protein content% (C), protein yield(D)

D1: 4.10⁴ plants. ha⁻¹, D2: 11.10⁴ plants. ha⁻¹ plants ha⁻¹, D3: 100.10⁴ plants. ha⁻¹. Data labelled with different letters are significantly different at P < 0.05

Correlation between the different parameters

In this study, we demonstrated a highly significant correlation between the studied parameters (Table 4): The number of capsules per plant and plant length (r = 0.89), the length of the capsules and the number of capsules per plant (r = 0.87), the number of seeds per capsule and the length of the capsules (r = 0.86), seed capsule length and weight (r = 0.82), protein content and seed yield (r = 0.95).

DISCUSSION

Growth parameters

Results showed that plant density had influenced sesame growth, yield, and biochemical properties. It was revealed that plant height had increased with plant density. This response of sesame under close spacing can be explained by the competition for light between adjacent plants in the field to maximize the capture and the use of light necessary for photosynthesis. Awais *et al.*, (2017) explained that photosynthetic rate and radiation penetration conversion into crop biomass regulate plant growth. Contrary results were obtained by Caliskan *et al.*, (2004) who used different plant sesame populations: 102,000; 127,500; 170,000; 255,000; 510,000, and found that plant height was shortened with increasing plant population. On the other hand, the reduction of root size under high plant density is consistent with the observation of Hébert *et al.*, (2001) and Liu *et al.*, (2012). York *et al.*, (2015) showed that high plant density altered roots in maize such as the number of nodal roots, the length of roots and the spatial distribution of root systems. However, wide spacing increased the capsules number per plant and the number of seeds per capsule. Similar results of our finding have been reported by Wang *et al.*, (2016) who showed that all these parameters were reduced by increasing the space between sunflowers. Van Roekel and Coulter, (2011) explained that the parameters for the capsules, especially the seed numbers, are an essential factor influencing the seed yield.

Table 3: Effect of plant density on concentration of P, K, Ca, Mg and Zn in the seed of sesame

	K (mg/100 g)	**P** (mg/100 g)	**Ca** (mg/100 g)	**Mg** (mg / 100 g)	**Zn** (mg/100 g)
D1	1532 ± 5.1 (a)	822 ± 2.7 (a)	1287 ± 3.2 (a)	283 ± 2.1 (a)	15.2 ± 1.3 (a)
D2	1487 ± 4.8 (a)	773 ± 1.9 (a)	1066 ± 3.0 (b)	27 ±4.2 (a)	14.8 ± 2.1 (b)
D3	1415 ± 4.6 (b)	677 ± 8.2 (b)	1000 ± 11.1 (c)	239 ± 3.2 (c)	14.7 ± 1.3 (bc)

D1: 4.10⁴ plants. ha⁻¹, D2: 11.10⁴ plants. ha⁻¹ plants ha⁻¹, D3: 100.10⁴ plants. ha⁻¹. Data labelled with different letters are significantly different at P < 0.05

Table 4: Matrix of correlation coefficients for parameters of sesame at different plant densities

	PH	**CN**	**SN**	**CL**	**SW**	**YS**	**BY**	**HI**	**O%**	**P%**	**OY**	**PY**
PH	1	0.88**	0.65	0.73*	0.85**	-0.83**	-0.80**	-0.33	0.70*	-0.84**	-0.33	-0.77*
CN	0.88**	1	0.57	0.76*	0.87**	-0.76*	-0.65	-0.41	0.73*	-0.76*	-0.50	-0.75*
SN	0.65	0.57	1	0.86**	0.62	-0.56	-0.80**	-0.07	0.18	-0.56	-0.40	-0.59
CL	0.77*	0.76*	0.86**	1	0.82**	-0.80**	-0.75*	-0.44	0.56	-0.77*	-0.56	-0.83**
SW	0.852**	0.71**	0.61	0.82**	1	-0.88**	-0.74*	-0.52	0.74*	-0.86**	-0.36	-0.80**
SY	-0.83**	-0.76*	-0.56	-0.87**	-0.88**	1	0.72*	0.70*	-0.65	0.99**	0.52	0.95**
BY	-0.80**	-0.65	-0.80**	-0.75*	-0.74*	0.72*	1	0.041	-0.47	0.74*	0.45	0.72*
HI	-0.33	-0.41	-0.07	-0.44	-0.52	0.70*	0.041	1	-0.38	0.68*	0.35	0.66
O%	0.70*	0.73*	0.18	0.56	0.74*	-0.65	-0.47	-0.38	1	-0.62	-0.28	-0.60
P%	-0.84**	-0.73*	-0.56	-0.77*	-0.86**	0.99**	0.74*	0.68*	-0.62	1	0.51	0.95**
OY	-0.35	-0.56	-0.40	-0.56	-0.36	0.52	0.45	0.35	-0.28	0.51	1	0.74*
PY	-0.77*	-0.78*	-0.59	-0.83**	-0.80**	0.95**	0.72*	0.66	-0.60	0.95**	0.74*	1

The results also showed a significant reduction in 1000-seed weight with increasing plant density and these findings agree with those of Wang *et al.* (2015) and Ozer, (2013) who suggested that 1000-seed weight is another factor that influences the seed yield of oilseed rape.

Yields parameters

It is clear from the data presented that seed yield increased with increasing plant density. This result may be attributed to the increase in the number of plants per unit area, which can compensate for the low yield per plant. Similar results were earlier reported in other crops, such as wheat (Li *et al.*, 2008) and canola (Wang *et al.*, 2011). Peltonen-Sainio *et al.* (2008) suggested that the number of seeds per capsule and the number of capsules per plant influences mostly seed yield per unit area. A study of Ibrahim (2012) revealed that high plant density had decreased individual plant characters but increased collective production per ha. As shown in the results, there was a strong relationship between seed yield, biological yield and harvest index. Yoshida (1972) considered that seed yield is related to biological yield through the harvest index. This result contradicts the finding of Caliskan *et al.*, (2004) who showed that increasing plant density significantly increases the harvest index of sesame.

Nutritional quality

The highest seed oil content was observed from the lowest plant density of 4.10^4 plants.ha^{-1}, whereas the lowest was obtained from the 100.10^4 plants.ha^{-1}. This effect of plantation density can be explained by the phenomenon of competition between plants for growth factors, which limits the biosynthesis and the accumulation of nutrients elements in seed such as the oil percentage of seeds. On the contrary, Brahim *et al.* (1998) reported that the seed oil content of *Lesquerella fendleri* at the plant density of 50 plant.m^{-2} was higher than at the plant density of 25 plant.m^{-2}, which might be due to the difference in crop species. However, the increase in oil yield ha^{-1} with higher plant density can be explained by the fact that it was compensated by increasing the number of plants per unit area.

For protein content, there was no significant difference between all plant densities, a result consistent with the Kondra (1977) who showed that the protein content did not change with varying plant density, but was contrary to the study of Caliskan *et al.*, (2004) and Shrief *et al.*, (1990) who reported that the protein content increases with the increase in plant density. However, protein yield increased with increasing plant density. The work of Berenguer and Faci (2001) with *Sorghum bicolor* showed that a reduction in individual seed quality was compensated on per hectare basis.

Higher nutrient uptake in the lowest plant density, 4.10^4 plants ha^{-1}, can be attributed to substantial increase in height and root size. In fact, Amato and Ritchie (2002) and Doussan *et al.* (2006) showed that the spatial distribution of root systems greatly affects the absorption of soil nutrients. Li *et al.*, (2012) reported that spatial root distribution indicates the potential for soil resource exploitation and absorption.

CONCLUSION

In summary, we conclude that the density of plantations constitutes a determinant agricultural practice for *Sesamum indicum*. Indeed, a wider spacing between plants favours some biological parameters, especially the number of capsules per plant, the number of seeds per capsule, the length of the capsules. At the same time, the increase in plant density did not allow each individual to achieve its equilibrium and benefit sufficiently from the environmental resources, leading to decreased productivity per plant. Nevertheless, this is compensated by an increase in the number of plants per unit area, and as a result, yields of seeds, oil, and protein per hectare increase with the narrow spacing. Consequently, the high density of 100.10^4 plants ha^{-1} could be recommended for better production per hectare of the sesame crop in the study area.

REFERENCES

Abou-Gharbia H.A., Shehata A.A.Y., Shahidi F. (2000). Effect of processing on oxidative stability and lipid classes of sesame oil. *Food Res. Int.,* 33: 331–340.

Amato M., Ritchie J.T. (2002). Spatial Distribution of Roots and Water Uptake of Maize (*Zea mays* L.) as Affected by Soil Structure. *Crop Sci.,* 42: 773–780.

Arslanoglu S.F., Sert S., Sahin H.A., Aytac S., El Sabagh A. (2022). Yield and yield criteria of flax fiber (*Linum usitatissimum* L) as influenced by different plant densities. *Sustainability*, 14: 1-3.

Awais M., Wajid A., Bashir M.U., Habib-ur-Rahman M., Raza M.A.S., Ahmad A., Saleem M.F., Hammad H.M., Mubeen M., Saeed U., Arshad M.N., Fahad S., Nasim W. (2017). Nitrogen and plant population change radiation capture and utilization capacity of sunflower in semi-arid environment. *Environ. Sci. Pollut. Res.*, 24: 17511–17525.

Bedigian D. (2003). Evolution of sesame revisited: domestication, diversity and prospects. Genet. Resour. *Crop Evol.,* 50: 779–787.

Berenguer M.J., Faci J.M. (2001). Sorghum (*Sorghum Bicolor* L. Moench) yield compensation processes under different plant densities and variable water supply. *Eur. J. Agron.,* 15: 43–55.

Brahim K., Ray D.T., Dierig D.A. (1998). Growth and yield characteristics of *Lesquerella fendleri* as a function of plant density. *Ind. Crops Prod.,* 9: 63–71.

Caliskan S., Arslan M., Halis A., Isler N. (2004). Effect of Planting Method and Plant Population on Growth and Yield of Sesame (*Sesamum indicum* L.) in a Mediterranean Type of Environment. *Asian J. Plant Sci.*, 3: 610-613.

Chen P.R., Chien K.L., Su T.C., Chang C.J., Liu T.L., Cheng H., Tsai C. (2005). Dietary sesame reduces serum cholesterol and enhances antioxidant capacity in hypercholesterolemia. *Nutrition research*, 25: 559-567.

Cooney R.V., Custer L.J., Okinaka L., Franke A.A. (2001). Effects of dietary sesame seeds on plasma tocopherol levels. *Nutr. Cancer,* 39: 66–71.

Cui C., Liu Y., Liu Y., Cui X., Sun Z., Du Z., Wu K., Jiang X., Mei H., Zheng Y. (2021). Genome-wide association study of seed coat color in sesame (*Sesamum indicum* L.). *PLoS ONE*, 16: e0251526.

Devkota M., Devkota K.P., Karrou M., Nangia V. (2023). Genotype and agronomic management interaction to enhance wheat yield and water use efficiency in the Mediterranean rainfed environment of Morocco: I. Field data analysis. *European Journal of Agronomy*, 151: 126972.

Doussan C., Pierret A., Garrigues E., Pagès L. (2006). Water Uptake by Plant Roots: II – Modelling of Water Transfer in the Soil Root-system with Explicit Account of Flow within the Root System – Comparison with Experiments. *Plant and Soil,* 283: 99–117.

FAOSTAT (2024). Statistical Database. Food and Agricultural Organization of the United Nations.

GhoreiShi A.S., ChAtrnour G., MAhMoodi M. (2022). The effect of sesame seeds on fast blood sugar, haemoglobin A 1C, liver enzymes and lipid profile in patients with type 2 diabetes: a randomised clinical trial. *Family Medicine et Primary Care Review*, 24(3).

Haque M.A., Sakimin S.Z. (2022). Planting arrangement and effects of planting density on tropical fruit crops—A Review. *Horticulturae*, 8: 485.

Hébert Y., Guingo E., Loudet O. (2001). The response of root/shoot partitioning and root morphology to light reduction in maize genotypes. *Crop Sci.,* 41: 363–371.

Ibrahim Hossam M.(2012). Response of some sunflower hybrids to different levels of plant density. APCBEE Procedia, 2nd International Conference on Asia Agriculture and Animal, 4: 175–182.

Khalid E.K., Babiker E.E., EL Tinay A.H. (2003). Solubility and functional properties of sesame seed proteins as influenced by pH and/or salt concentration. *Food Chem.,* 82: 361–366.

Kondra Z.P. (1977). Effects of planted seed size and seeding rate on rapeseed. *Can. J. Plant Sci.,* 57: 277–280.

Li H.-B., Zhang F.-S., Shen J.-B. (2012). Contribution of root proliferation in nutrient-rich soil patches to nutrient uptake and growth of maize. *Pedosphere,* 22: 776–784.

Li Q., Chen Y., Liu M., Zhou X., Yu S., Dong B. (2008). Effects of irrigation and planting patterns on radiation use efficiency and yield of winter wheat in North China. *Agric. Water Manag.,* 95: 469–476.

Lisson S.N., Mendham N.J. (2000). Agronomic studies of flax (*Linum usitatissimum* L.) in south-eastern Australia. *Australian Journal of Experimental Agriculture*, 40: 1101-1112.

Mohamed H.M.A., Awatif I.I. (1998). The use of sesame oil unsaponifiable matter as a natural antioxidant. *Food Chem.,* 62: 269–276.

Sallam K.I., Abd-Elghany S.M., Imre K., Morar A., Herman V., Hussein M.A., Mahros M.A. (2021). Ensuring safety and improving keeping quality of meatballs by addition of sesame oil and sesamol as natural antimicrobial and antioxidant agents. *Food Microbiology,* 99: 103834.

Shrief S.A., Shabana R., Ibrahim A.F., Geisler G. (1990). Variation in seed yield and quality characters of four spring oil rapeseed cultivars as influenced by population arrangements and densities. *J. Agron. Crop Sci.,* 165: 103–109.

Shyu Y.-S., Hwang L.S. (2002). Antioxidative activity of the crude extract of lignan glycosides from unroasted Burma black sesame meal. *Food Res. Int.,* 35: 357–365.

Teklu D.H., Shimelis H., Abady S. (2022). Genetic improvement in sesame (*Sesamum indicum* L.): Progress and outlook: A review. *Agronomy*, 12: 2144.

Turner J.A. (1991). Linseed plant population relative to cultivar and fertility. *Aspects Appl. Biol.*, 28: 41-48.

Van Roekel R.J., Coulter J.A. (2011). Agronomic responses of corn to planting date and plant density. *Agron. J.,* 103: 1414–1422.

Wang X., Hou Y., Du M., Xu D., Lu H., Tian X., Li Z. (2016). Effect of planting date and plant density on cotton traits as relating to mechanical harvesting in the Yellow River valley region of China. *Field Crops Res.,* 198: 112–121.

Were B.A., Onkware A.O., Gudu S., Welander M., Carlsson A.S. (2006). Seed oil content and fatty acid composition in East African sesame (*Sesamum indicum* L.) accessions evaluated over 3 years. *Field Crops Res.,* 97: 254–260.

Yoshida S. (1972). Physiological aspects of grain yield. *Annu. Rev. Plant Physiol.,* 23: 437–464.

Zhao F., McGrath S.P., Crosland A.R. (1994). Comparison of three wet digestion methods for the determination of plant sulphur by inductively coupled plasma atomic emission spectroscopy (ICP-AES). *Commun. Soil Sci. and Plant Analysis,* 25: 407–418.