







Climate change necessitates a change in the cultivation date of caraway (*Carum carvi* L.)

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Abstract: By 2050, global crop demand is projected to rise by 60–110%. Crop yields have also been impacted by climate change in some nations, and these impacts are likely to continue. To prevent the influence of climate change on crop output, it is critical to adjust planting times in weather-related open fields to meet food security concerns. Present study was carried out at Experimental Farm of Faculty of Agriculture, Al-Azhar University, Assiut, Egypt, during two successive seasons, 2019 and 2020. It was aimed to study the effect of different sowing times (1st and 15th October, 1st and 15th November), and plant spacings (25, 20, and 15 cm) on growth, fruit yield, and oil production of caraway (*Carum carvi* L.) plants. The results showed that sowing caraway plants on 15th October with plant spacing of 25 cm gave the highest dry weight (72.6 g·plant⁻¹), fresh weight (266.15 g·plant⁻¹), seed yield (37.43 g·plant⁻¹), and oil yield (0.659 cm³·plant⁻¹). The maximum umbels (50.83 number per plant) and essential oil (1.78%) were also recorded in the plants receiving same treatment. On the other hand, plants sown at 15th November with spacing of 15 cm exhibited the minimum values of recorded traits. While the highest value of plant height gave with sowing caraway plants on 15th October with plant spacing of 15 cm (135.35 cm). In conclusion, the plants sowed on October 15th with a maximum plant spacing of 25 cm had the highest values of the evaluated morphological, biochemical, and yield attributes of caraway.

Keywords: climate change, condiments, leafy vegetables, sowing time, vegetative growth, volatile oil

INTRODUCTION

Caraway (*Carum carvi* L.) belongs to the family Umbelliferae (Apiaceae), is an annual winter herb [PETER (ed.) 2006]. It is one of the drugs and condiment crops and has a particular importance among the medicinal plants in some parts of the world [SACHAN *et al.* 2016]. It occurs both wild and domesticated in central and northern Europe, Egypt, Morocco, Australia, and China [RUBATZKY *et al.* 1999]. Caraway fruits were known to Arabian physicians and probably came into use in Europe in the thirteenth century [EVANS 2009]. The dried fruit, commonly called

seeds, contains 2–8% essential oil [LAWLESS 2013]. Carvone and limonene are the principal components, besides, trace amounts of other constituents (such as acetaldehyde, furfural, carveol, pinene, thujone, camphene, phellandrene, hydrocarbons, γ -terpinene, etc.) are also present. Caraway seeds also contain lipids (13–21%), nitrogenous compounds (25–35%), fibers (13–19%), and water (9–13%) [EZZ EL-DIN *et al.* 2010].

The best way to achieve the economical goal is to increase yield by using the proper cultivars, best sowing date and optimum plant density [BEGNA, ANGADI 2016]. Plant density depends on the growth cycle, time and method of cultivation, soil conditions,

sunlight and allelopathic surroundings of the plant [ALVES SOUZA *et al.* 2020]. Selection of suitable sowing date has advantages concerning assembling the raw material and other productions. Some studies of planting dates in *Hibiscus sabdariffa* found that the early planting dates gave the highest plant height, branches, biomass, sepals, seeds as well as increased N, P, K, and total carbohydrates percentage, acidity, anthocyanins and fixed oil [FUTULESS *et al.* 2010; OYEWOLE, MERA 2010]. On the other hand, some previous authors conducted experiments to determine the appropriate row spacing in fennel (*Foeniculum vulgare* Mill.) crop, indicating that plant seeding at the nearest distance had a positive effect on plant growth, seed yields, oil production and plant chemical components, and produced the highest seed yield compared to control plants [KHORSHIDI *et al.* 2009; MENARIA, MALIWAL 2011].

The effect of sowing time and seed spacing was studied by many investigators on fennel plants. In this respect, the studies of EL-KHAYYAT and GOUDA [2005], KUMAR *et al.* [2006], AYUB *et al.* [2008], SINGH *et al.* [2009] and SELIM *et al.* [2013] verified that early sowing had a positive impact on plant growth, seed yield, oil production, and phytochemical components of fennel plants from the beginning of October to mid-October.

Optimum sowing date and plant spacing had positive effects on growth, yield and chemical composition of different plant species as emphasised by many authors (THALJI and SHALALDEH [2006] on faba bean (*Vicia faba*) and SAJJAD *et al.* [2014] on quinoa (*Chenopodium quinoa*)). However, BHARGAVA *et al.* [2007] and SIEF *et al.* [2015] found that the best growth and yield of quinoa was obtained when plant were sown at 15th October with spacing of 25 cm, while late sowing (1st December) gave the lowest yield regardless of plant spacing. Similarly, EISA *et al.* [2018] reported that, quinoa plant sown at low density (56,000 plant·ha⁻¹) showed significant increase in seed weight as compared to control, and 100 dm³ were obtained due to differences in temperature, rainfall and radiation over the year.

Sowing time is a key factor in the flowering phase of plants; delayed sowing can reduce the number of flowers [NLEYA *et al.* 2020]. By changing day length, maximum and minimum temperatures, relative humidity, and other environmental conditions during the growing season, changing the sowing date can impair plant fertility [SHRESTHA *et al.* 2018]. The length of the growth cycle, phenological processes, and finally the quantitative and qualitative yield of plants can also be influential [DADKHAH *et al.* 2010].

The goal of the present study was to explore the effects of different sowing times and plant spacings on morphological characteristics and yield of caraway plants, and to define the best treatment for maximum quantitative and qualitative crop output.

MATERIALS AND METHODS

EXPERIMENTAL SITE

During two consecutive growing seasons (2018/2019 and 2019/2020), field experiments were performed at the Experimental Farm of the College of Agriculture, Al-Azhar University, Assiut, Egypt to evaluate the impact of sowing time and plant spacing on the morphological and biochemical traits of caraway (*Carum carvi* L.). Soil (30 cm upper layer) from both experimental locations was analysed according to YANCEY *et al.* [1982] and KLUTE [1986] (Tab. 1).

Table 1. The initial physio-chemical properties of the experimental soil during both growing seasons

Parameter		Value in years	
		2018/2019	2019/2020
Particle size distribution	sand (%)	20.0	18.3
	silt (%)	56.5	59.6
	clay (%)	23.5	22.1
Texture grade		silty loam	silty loam
pH of soil water suspension (1:2.5) (w/v)		7.5	7.3
EC _e (dS·m ⁻¹) soil paste		2.2	2.0
OM (%)		0.50	0.60
Total CaCO ₃ (%)		2.53	2.43
HCO ₃ ⁻ (cmol·kg ⁻¹ of soil)		2.9	3.2
Cl ⁻ (cmol·kg ⁻¹ of soil)		2.2	2.1
SO ₄ ²⁻ (cmol·kg ⁻¹ of soil)		6.6	6.4
Ca ²⁺ (cmol·kg ⁻¹ of soil)		3.4	3.6
Mg ²⁺ (cmol·kg ⁻¹ of soil)		1.9	2.3
K ⁺ (cmol·kg ⁻¹ of soil)		3.5	3.35
Na ⁺ (cmol·kg ⁻¹ of soil)		22.72	18.07

Explanations: each value represents a mean of three replicates, EC = electrical conductivity, OM = organic matter. Source: own study.

EXPERIMENTAL DESIGN AND TREATMENTS

The study was carried out as a bifactorial experiment based on a randomised complete block design with three replications. The factors included “sowing time” (main plot) i.e., 1st Oct, 15th Oct, 1st Nov and 15th Nov, and “plant spacing” (subplot) i.e., 15, 20 and 25 cm. Caraway seeds were obtained from the Medicinal and Aromatic Plant Research Department, El-Kanater El-Khairia, El-Kaliobia, Egypt. The soil was prepared by plowing twice orthogonally, flattening, and dividing the experimental units. The experimental area was 2 × 3 m containing four rows (the distance between rows was 60 cm). Plants were thinned (two plants per hole) after 21 days of planting. The plants were irrigated monthly, according to the needs of the plant and the type of soil. At 25 and 55 days after sowing (DAS) in both growing seasons, weeds were removed manually. The prescribed basal dose of P₂O₅ i.e., 107 kg·ha⁻¹ (15.5% CaH₆O₉P₂) was incorporated into the soil. While 159.46 kg N·ha⁻¹ (33.5% NH₄NO₃) and 119 kg·ha⁻¹ K₂O (50% potassium sulphate) were divided into two equivalent splits at 30 and 60 DAS, as recommended by the Ministry of Agriculture, Egypt [HASSAN 2011].

WEATHER CONDITIONS DURING THE EXPERIMENT

According to Köppen–Geiger climate map, the climate of the experimental region (Assiut city, Egypt) is described as very hot and dry in summer and as cold in winter [BECK *et al.* 2018]. Maximum and minimum temperatures and relative humidity during the two growing seasons are shown in Figure 1.

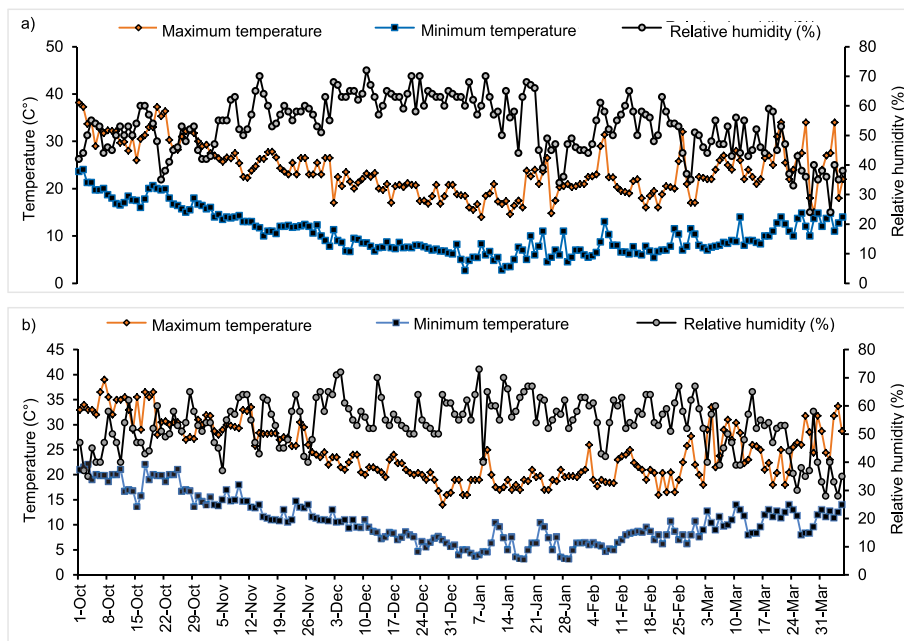


Fig. 1. Weather conditions during the two growing seasons of caraway cultivation: a) growing season 2018/2019, b) growing season 2019/2020; source: own study

DATA COLLECTION

In both growing seasons, data regarding growth parameters were collected after 152, 154, 152 and 140 days of 1st, 2nd, 3rd and 4th sowing, respectively. Plant height was measured at the end of the experiment from the soil surface to the top of each plant for the different treatments. Plant height was taken using a ruler from the base of the rhizome to the top of the plant, whereas the average was calculated and recorded just before harvesting. The fresh and dry weights of the plants and seed yield weight were weighed using an electronic balance (MJ-W176P). In all treatments, the dry weight of the plant was obtained by oven drying at 75°C until a constant weight was obtained [SORGONA *et al.* 2011]. The oil production was determined at the end of experiment for the both seasons according to BPC 2009, by water distillation of 100 g of seed for 1.5–2.0 h to extract the essential oil. Finally, the essential oil yield was determined by the formula of FARAHANI *et al.* [2008], where volatile oil yield (cm³·plant⁻¹) was calculated by multiplying volatile oil (% in seed weight, g·plant⁻¹).

STATISTICAL ANALYSIS

Collected data were subjected to two-way ANOVA (sowing time-plant spacing) using statistical software package “Statistics 8.1” [GOMEZ, GOMEZ 1984; SNEDECOR, COCHRAN 1989]. The treatments’ means were compared using Fisher’s Least significant difference (LSD) test at the significance level of 5% ($p \leq 0.05$) [DADKHAH *et al.* 2010].

RESULTS

MORPHOLOGICAL TRAITS

The results revealed that the sowing time and plant spacing exhibited significant impact on morphology of caraway plants. During 1st growing season (2019), plants sown on 15th Oct

showed maximum height (132.83 cm) among those were sown on other dates, late sowing on 15th Nov caused (6.5%) reduction. Concerning the plant spacing, 15 cm was the best treatment with respect to plant height (131.51 cm). The maximum plant height (135.2 cm) was reported in the plants seeded on the 15th of Oct with plant spacing of 15 cm, when the cumulative impact of sowing time and plant spacing was considered. Similarly, in 2nd season, the maximum height was observed in caraway plants sown at 15th Oct (135.5 cm) with plant spacing of 25 cm. In case of number of branches, the plants sown earlier (15th Oct and 1st Nov) showed the highest number (25.98 and 25.05, respectively) during 1st growing season. Plant spacing also influenced this trait significantly, showing the highest average number of branches (26) in the plants sown at 25 cm spacing. In both growth seasons, the interplay between sowing time and plant spacing had a significant influence on the quantity of caraway branches (Tab. 2). Based on the results shown in Table 2, the highest number of umbels per plant (45.56 and 48.65) were recorded in the plants sown on 15th Oct in both growing seasons, respectively. Plant spacing also had significant impact on number of umbels. Maximum umbels was recorded in the plants sown at the distance of 25 cm (44.72 and 48.07 during 2019 and 2020, respectively). Because of the interaction between sowing time and spacing, the quantity of umbels per plant varied significantly. The maximum number of umbels per plant was observed in the plants sown on 15th Oct with planting distance of 25 cm during 1st and 2nd growing season.

The results in Table 3 demonstrated that sowing time and plant spacing had a substantial influence on biomass of caraway plants. During 1st growing season (2019), plants sown on 15th Oct showed maximum dry weight per plant (67.90 g·plant⁻¹) among those were sown on other dates, while the late sowing on 15th Nov showed minimum of dry weight (60.32 g·plant⁻¹). Referring to the plant spacing, 25 cm was the best treatment with relevance to dry weight (67.66 g·plant⁻¹). The maximum dry weight (72.1 g·plant⁻¹) was obtained in the plants seeded on the 15th of Oct with a 25 cm

Table 2. Effect of sowing time and plant spacing on plant height, number of branches and number of umbels per plant of caraway during two growing seasons

Sowing time		Plant height (cm) at plant spacing			Mean (A)	Number of branches per plant at plant spacing			Mean (A)	Number of umbels per plant at plant spacing			Mean (A)	
		25 cm	20 cm	15 cm		25 cm	20 cm	15 cm		25 cm	20 cm	15 cm		
2019	1 st Oct	126.6 def	130.3 bcd	132.4 ab	129.75 b	26.0 bcd	25.2 bcd	22.9 def	24.68 a	42.7 cd	40.5 cd	37.5 d	40.22 b	
	15 th Oct	131.3 abc	132.0 abc	135.2 a	132.83 a	28.4 a	26.2 abc	23.4 bcd	25.98 a	48.5 a	44.9 ab	43.3 bc	45.56 a	
	1 st Nov	128.3 bc	132.2 abc	133.5 ab	131.33 ab	26.5 ab	25.5 a-d	23.2 bcd	25.05 a	45.4 ab	43.3 bc	41.8 bc	43.5 a	
	15 th Nov	125.1 efg	123.3 fg	121.6 g	123.32 c	22.9 c-f	21.3 ef	19.7 f	21.3 b	42.3 bc	39.9 cd	37.4 d	39.84 b	
	mean (B)		126.95 c	129.45 b	131.51 a	–	26.0 a	25.2 a	22.9 b	24.68 a	44.72 a	42.15 b	39.97 c	–
	LSD (p ≤ 0.05)	A	2.16				1				1.5			
B		1.24				1.058				1.0				
A×B		2.4				1.8				1.9				
2020	1 st Oct	128.2 b	133.4 a	135.1 a	132.21 b	27.5 b	26.1 bc	24.8 cd	26.11 b	46.9 b	43.6 bc	40.1 c	43.52 c	
	15 th Oct	133.9 a	134.8 a	135.5 a	134.72 a	29.3 a	27.3 abc	24.7 cd	27.07 a	53.2 a	47.5 ab	45.3 bc	48.65 a	
	1 st Nov	133.8 a	134.6 a	134.7 a	134.36 a	28.7 ab	27.1 abc	25.2 bcd	26.96 a	48.5 ab	45.3 bc	43.0 bc	45.62 b	
	15 th Nov	124.9 c	127.8 bc	128.5 b	127.05 c	24.4 cde	22.3 de	21.1 e	22.61 c	43.7 bc	41.1 c	39.6 c	41.47 d	
	mean (B)		130.19 b	132.65 a	133.42 a	–	27.46 a	25.68 b	23.91 c	–	48.07a	44.38 b	42.0 c	–
	LSD (p ≤ 0.05)	A	1.18				1.2				2.2			
B		0.86				0.87				1.5				
A×B		2.9				1.8				3.0				

Explanations: A = plant spacing, B = sowing time; values shown in the table are the means of three replicates; LSD = least significant difference; different letters indicate significant differences among treatments according to Duncan's multiple range test when $p \leq 0.05$. Source: own study.

Table 3. Effect of sowing time and plant spacing on dry weight, fresh weight and 1000-seeds weight of caraway during two growing seasons

Sowing time		Dry weight (g·plant ⁻¹) at plant spacing			Mean (A)	Fresh weight (g·plant ⁻¹) at plant spacing			Mean (A)	1000-seeds weight (g) at plant spacing			Mean (A)	
		25 cm	20 cm	15 cm		25 cm	20 cm	15 cm		25 cm	20 cm	15 cm		
2019	1 st Oct	68.6 b	63.0 de	60.1 f	63.92 c	248.2 bc	231.0 de	220.5 f	233.23 c	8.97 bc	8.75 bcd	8.12 d	8.61 c	
	15 th Oct	72.1 a	68.0 bc	63.6 d	67.90 a	264.4 a	249.3 bc	233.1 d	248.91 a	9.73 a	9.35 ab	9.16 abc	9.41 a	
	1 st Nov	68.8 b	66.6 c	61.2 ef	65.52 b	252.1 b	244.1 bc	224.5 ef	240.23 b	9.13 abc	9.04 bc	8.67 cd	8.94 b	
	15 th Nov	61.1 ef	59.9 f	59.7 f	60.23 d	224.0 ef	219.6 f	218.8 f	220.77 d	8.16 d	7.08 e	6.85 e	7.36 d	
	Mean (B)		67.66 a	64.36 b	61.15 c	–	247.16 a	235.98 b	224.21 c	–	9 a	8.55 b	8.19 c	–
	LSD (p ≤ 0.05)	A	1.1				4.7				4.7			
B		1.7				5.88				5.88				
A×B		3.4				11.6				11.6				
2020	1 st Oct	69.8 b	66.4 cd	61.5 f	65.91 b	250.5 bc	237.9 d	225.5 ef	237.95 c	9.07 bcd	8.92 cde	8.36 e	8.78 c	
	15 th Oct	73.1 a	69.1 bc	65.3 de	69.14 a	267.9 a	253.3 bc	239.3 d	253.48 a	9.96 a	9.64 ab	9.37 abc	9.65 a	
	1 st Nov	69.4 b	67.3 bcd	62.8 de	66.51 b	254.6 b	246.7 c	230.1 e	243.78 b	9.32 a-d	9.16 bcd	8.95 cde	9.14 b	
	15 th Nov	62.2 f	61.0 f	60.1 f	65.9 c	228.1 e	223.8 e	220.5 ef	224.13 d	8.68 de	7.25 f	6.99 f	7.64 d	
	Mean (B)		68.63 a	65.96 b	62.425 c	–	250.27 a	240.40 b	228.84 c	–	9.25 a	8.74 b	8.41 c	–
	LSD (p ≤ 0.05)	A	1.6				4.3				4.3			
B		1.4				4.4				4.4				
A×B		2.8				8.9				8.9				

Explanations as in Tab. 2. Source: own study.

spacing, taking into account the interaction impact of sowing time and plant spacing. Similarly, in 2nd season, the maximum dry weight per plant was observed in caraway plants sown at 15th Oct (73.1 g·plant⁻¹) with plant spacing of 25 cm. In case of fresh weight, the plants sown earlier (15th Oct) showed the highest weight (248.91 g·plant⁻¹) during 1st growing season. Plant

spacing also influenced this trait significantly, showing the highest average fresh weight ($247.16 \text{ g}\cdot\text{plant}^{-1}$) in the plants sown at 25 cm spacing. In both growth seasons, the combination between sowing time and plant spacing had a significant influence on fresh weight of caraway per plant (Tab. 3). Based on the results shown in Table 3, the highest weight of 1000 seeds (9.41 and 9.65 g) were recorded in the plants sown on 15th Oct in both growing seasons, respectively. Plant spacing also had significant impact on 1000-seeds weight (g). Maximum weight was recorded in the plants sown at the distance of 25 cm (9 and 9.25 g during 2019 and 2020, respectively). The interaction of sowing time and spacing resulted in significant weight fluctuations in 1000 seeds. During the first and second growth seasons, plants seeded on 15th Oct with a planting spacing of 25 cm had the highest weight of 1000 seeds.

YIELD AND BIOCHEMICAL TRAITS

The sowing time and plant spacing exhibited significant impact on seeds yield of caraway plants. Plants seeded on the 15th Oct had the highest seed weight per plant ($31.47 \text{ g}\cdot\text{plant}^{-1}$) among those sown on other dates during the first growing season (2019), while late sowing on the 15th of Nov had the lowest seed weight per plant ($22.02 \text{ g}\cdot\text{plant}^{-1}$). Concerning the plant spacing, 25 cm was the best treatment with respect to seed weight ($30.85 \text{ g}\cdot\text{plant}^{-1}$). Considering the cumulative effect of sowing time and plant spacing, the maximum seed weight ($36.2 \text{ g}\cdot\text{plant}^{-1}$) was recorded in the plants sown on 15th Oct with plant spacing of 25 cm (Fig. 2a). Similarly, in 2nd season, the maximum seeds weight per plant was observed in caraway plants sown at 15th Oct ($38.7 \text{ g}\cdot\text{plant}^{-1}$) with plant spacing of 25 cm. In case of seed weight per hectare, the plants sown earlier (15th Oct) showed the highest weight ($2291.72 \text{ kg}\cdot\text{ha}^{-1}$) during 1st growing season. Plant spacing had a substantial impact on this feature, with 20 cm

spacing producing the greatest average seed weight per hectare ($2041.56 \text{ g}\cdot\text{plant}^{-1}$). The interaction between sowing time and plant spacing had also a remarkable impact seed weight of caraway per hectare in both growing seasons (Fig. 2b).

During 1st growing season (2019), plants sown on 15th Oct showed maximum value of volatile oil (1.51%) among those were sown on other dates. When it came to plant spacing, 25 cm was the greatest option for volatile oil (1.60%). The most volatile oil (1.70%) was obtained in the plants seeded on the 15th of Oct with a plant spacing of 25 cm, when the cumulative impact of sowing time and plant spacing was considered (Fig. 3a). While, in 2nd season, the maximum volatile oil percentage was observed in caraway plants sown at 1st Nov and 15th Oct (1.90 and 1.86%, respectively) with plant spacing of 25 cm (Fig. 3b). In case of volatile oil yield $\text{cm}^3\cdot\text{plant}^{-1}$, the plants sown earlier (15th Oct) showed the highest yield ($0.478 \text{ cm}^3\cdot\text{plant}^{-1}$) during 1st growing season. Plant spacing also influenced this trait significantly, showing the highest average of volatile oil yield ($0.497 \text{ cm}^3\cdot\text{plant}^{-1}$) in the plants sown at 25 cm spacing. In both growth seasons, the interaction between sowing time and plant spacing had a significant influence on volatile oil output per plant; the greatest volatile oil yields (0.599 and $0.719 \text{ cm}^3\cdot\text{plant}^{-1}$) were reported during the first and second growing seasons, respectively (Fig. 3c, d).

The highest value of volatile oil yield expressed in cubic decimeters per hectare (34.32 and $40.29 \text{ dm}^3\cdot\text{ha}^{-1}$) were recorded in the plants sown on 15th Oct in both growing seasons, respectively. The amount of volatile oil output in cubic decimeters per hectare was similarly affected by plant spacing. The plants seeded at a distance of 25 cm had the highest value (29.51 and $34.27 \text{ dm}^3\cdot\text{ha}^{-1}$ during 2019 and 2020, respectively). Significant differences in volatile oil yield expressed in cubic decimeters per hectare emerged from the interaction of planting timing and spacing. The maximum average of volatile oil yield in cubic

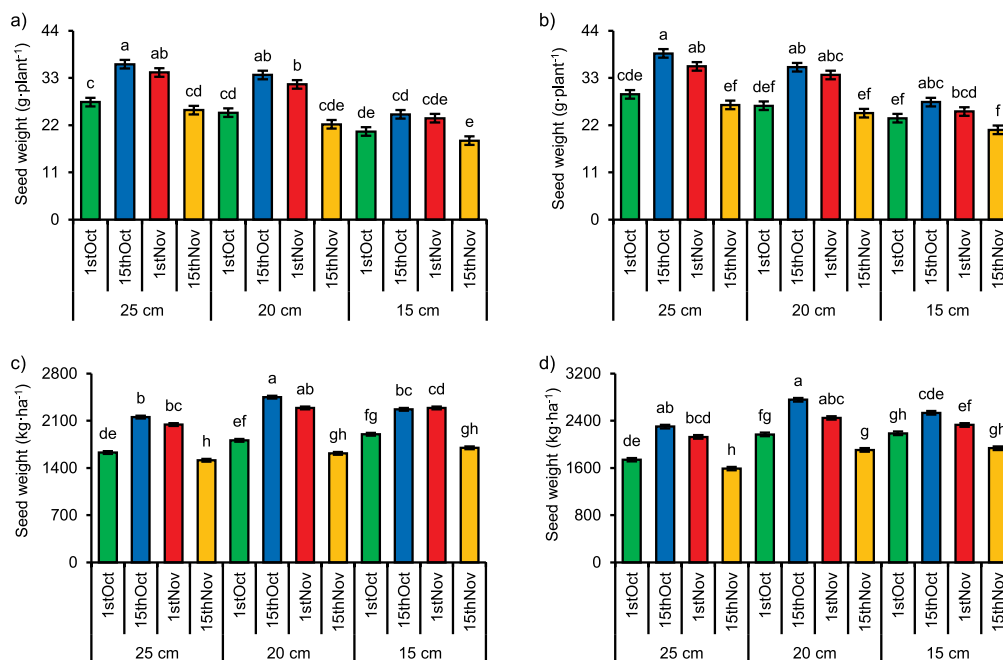


Fig. 2. Effect of sowing time and plant spacing on seed weight of caraway during two growing seasons: a) seed weight ($\text{g}\cdot\text{plant}^{-1}$) season 2019, b) seed weight ($\text{g}\cdot\text{plant}^{-1}$) season 2020, c) seed weight ($\text{kg}\cdot\text{ha}^{-1}$) season 2019, d) seed weight ($\text{kg}\cdot\text{ha}^{-1}$) season 2020; different letters indicate significant differences among treatments according to Duncan's multiple range test when $p \leq 0.05$; source: own study

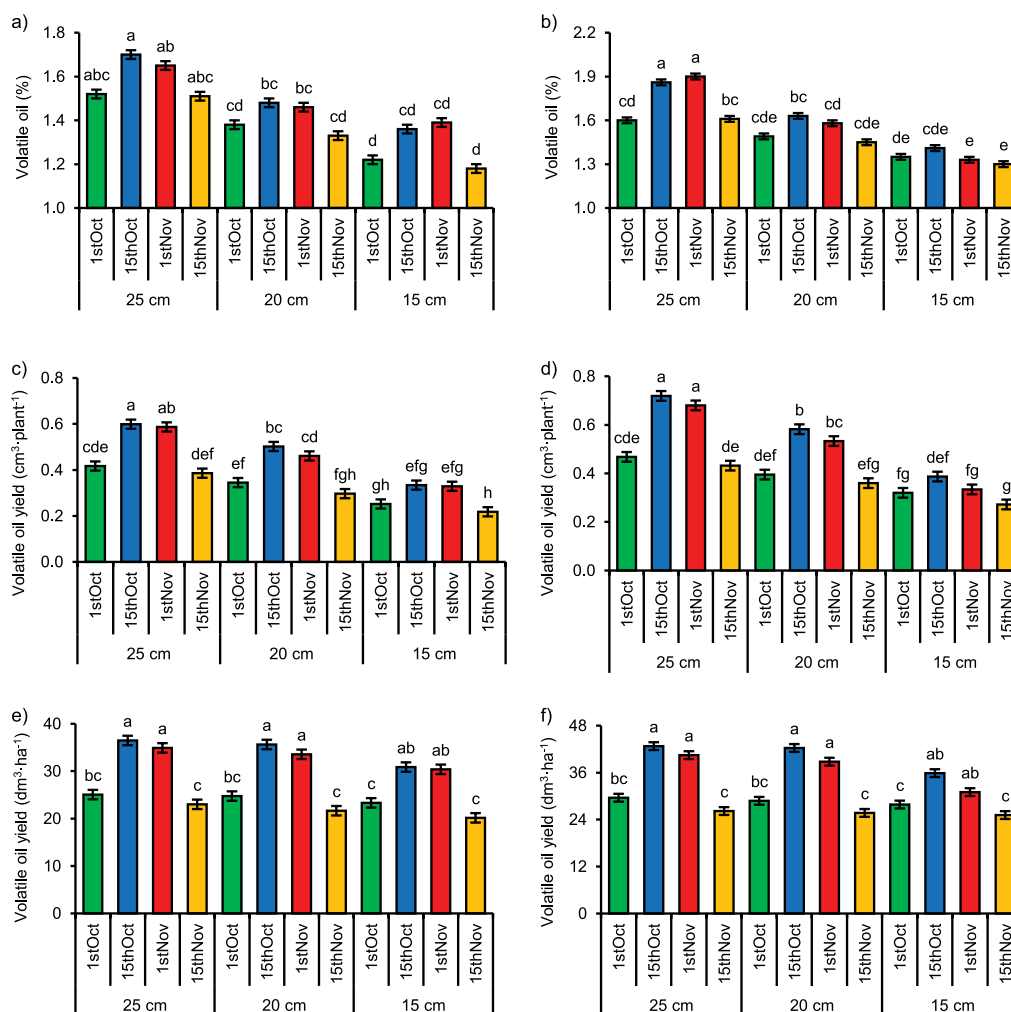


Fig. 3. Effect of sowing time and plant spacing on volatile oil (%) and oil yield ($\text{cm}^3 \cdot \text{plant}^{-1}$ and $\text{dm}^3 \cdot \text{ha}^{-1}$) of caraway during two growing seasons: a) volatile oil (%) season 2019, b) volatile oil (%) season 2020, c) volatile oil yield ($\text{cm}^3 \cdot \text{plant}^{-1}$) season 2019, d) volatile oil yield ($\text{cm}^3 \cdot \text{plant}^{-1}$) season 2020, e) volatile oil yield ($\text{dm}^3 \cdot \text{ha}^{-1}$) season 2019, f) volatile oil yield ($\text{dm}^3 \cdot \text{ha}^{-1}$) season 2020; different letters indicate significant differences among treatments according to Duncan's multiple range test when $p \leq 0.05$; source: own study

decimeters per hectare was observed in the plants sown on 15th Oct with planting distance of 25 cm (36.48 and $42.76 \text{ dm}^3 \cdot \text{ha}^{-1}$) during 1st and 2nd growing season, respectively (Fig. 3e, f).

DISCUSSION

Genetic and agronomic variables impact the development and output of medicinal plants [YUAN *et al.* 2020]. One of the most important success factors in agriculture is choosing the most acceptable sowing time and planting density [MARESMa *et al.* 2019; MOOSAVI *et al.* 2015]. The increase in plant height following the increase in plant density tends to cause the rise in inter-plant light rivalry and the disturbance of the balance of growth regulators [CRAINE, DYBZINSKI 2013]. The reduction in light penetration into the middle and lower layers of the canopy reduces auxin decomposition [CASAL 2013], thus, under these conditions, if other environmental factors such as moisture and soil fertility restrict the growth of plants, plant height increases [IMAM, RANJBAR 2000]. For each crop, there is an idealistic sowing time,

further delay can typically reduce the yield [PATEL *et al.* 2019]. Experts in agriculture believed that the cornerstone of a successful agronomic system is the establishment of an acceptable density of healthy plants at farm level [SHEKARA *et al.* 2016]. The increase in the number of plants per unit area causes fierce competition between plants over environmental variables such as light, nutrients, and humidity. Similarly, the decrease of the number of plants per unit area causes to the lack of economic return from the crop [CRAINE, DYBZINSKI 2013]. In current study, the plants sown in mid-October with planting distance of 25 cm showed dominant growth and development among other treatments (Fig. 4).

Our results provide light on the importance of plant spacing and sowing time in boosting the caraway plant's qualitative and quantitative production, as well as the effectiveness of combining these treatments to change the features evaluated in these plants. The maximum yield is understood to derive from the most favourable environmental conditions for each crop [LILIANE, CHARLES 2020]. In our present experience, the plants seeded on 15th Oct were exposed to the optimal short-day period, optimum

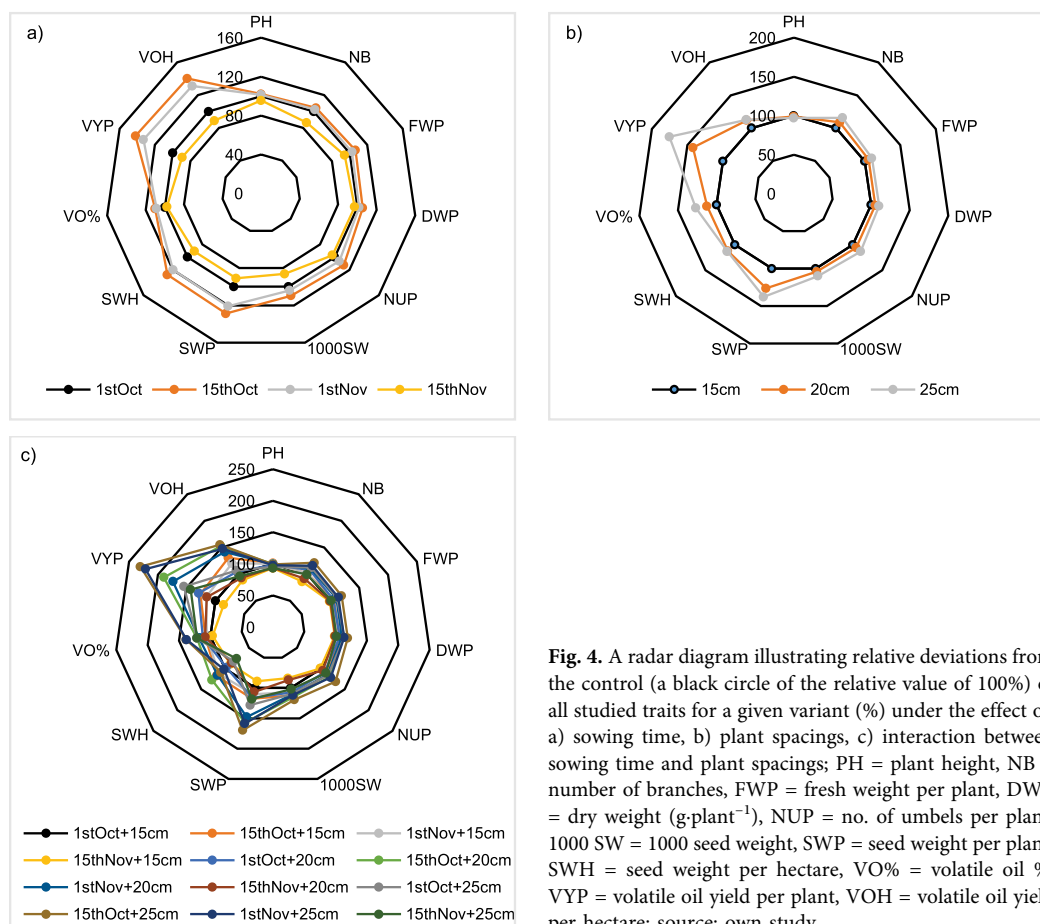


Fig. 4. A radar diagram illustrating relative deviations from the control (a black circle of the relative value of 100%) of all studied traits for a given variant (%) under the effect of: a) sowing time, b) plant spacings, c) interaction between sowing time and plant spacings; PH = plant height, NB = number of branches, FWP = fresh weight per plant, DWP = dry weight ($\text{g}\cdot\text{plant}^{-1}$), NUP = no. of umbels per plant, 1000 SW = 1000 seed weight, SWP = seed weight per plant, SWH = seed weight per hectare, VO% = volatile oil %, VYP = volatile oil yield per plant, VOH = volatile oil yield per hectare; source: own study

low temperature, and optimum high moisture availability, as shown in Figure 1. This might explain the higher yield. They had greater vegetative growth and cell division, which contributed to increased stem elongation, particularly in the stems. SINGH *et al.* [2005] found a reduction in plant height in fenugreek plants (*Trigonella foenum-graecum*) whose seeding was postponed from October to November. Late-sown safflowers had smaller plant diameters, resulting in a drop in sap production, according to AMIRI [2003]. This was due to the conjunction of the long day period and higher temperatures, according to AMIRI [2003]. The appropriate climatic circumstances and surroundings of components may boost biosynthetic processes and photosynthesis to produce excellent plants, which might explain the findings [HIRICH *et al.* 2014; SAJJAD *et al.* 2014; WANG *et al.* 2020]. The low below and above ground competition between plants for light, water, and nutrients may explain the rise in these features with increased plant spacing between caraway plants. These results are in accordance with those obtained by BADRAN *et al.* [2007] on fennel plants, and BHARGAVA *et al.* [2007] and SIEF *et al.* [2015] on quinoa plants, they reported that plant density is one of the important factors that affect the final yield. Increased planting distances up to 15 cm wide resulted in a drop in grain output. Growth and yield were reduced due to changes in radiation, daylight hours, and an unfavourable seed temperature. The importance of the proper season and time of sowing is irreplaceable in all other agronomic managements, and the advantage of adequate sowing time has been recorded in numerous agricultural settings [KADHUM 2009; MOHAMMADGHASE-

MI *et al.* 2021]. The lower fixed oil output with crops planted after 1st Nov might be attributed to the crops' poor environment for oil biosynthesis. Early seeding increased essential oil yields, perhaps due to favourable climatic inputs that boosted essential oil production, resulting in more plant metabolites. According to ELMEKAWY [2012], essential oil content is always higher when the crop is sown early.

Abiotic stress factors such as heat, soil salinity, drought, tropospheric ozone, and excessive UV radiation are already causing major agricultural yield declines, and due to the impact of global climate change, they will become even more pronounced in the coming decades – Figure 5 [ASHMORE 2006; FENG, KOBAYASHI, 2009; WASSMANN *et al.* 2009a]. Climate change is the incidence of unfavourable environmental conditions and has prompted efforts around the world to adjust agricultural activity to these stresses [ELSHEERY, CAO 2008; ELSHEERY *et al.* 2020a, b, c; HELALY *et al.* 2017; LOBELL *et al.* 2008; NASER *et al.* 2016; WASSMANN *et al.* 2009b]. Physiological shifts in crop plants as a result of exposure to abiotic stresses entail changes in photosynthetic gas exchange and assimilate translocation [MORGAN *et al.* 2004], altered water absorption and evapotranspiration, impacts on nutrient uptake and translocation [SÁNCHEZ-RODRÍGUEZ *et al.* 2010], antioxidant reactions [BRAY 2000], programmed cell death [KANGASJÄRVI 2005], and altered gene expression and enzyme activity [DURRETT *et al.* 2007; FREI *et al.* 2010]. These exposures are expected to have a variety of impacts on seed chemical composition and, as a result, agricultural product content.

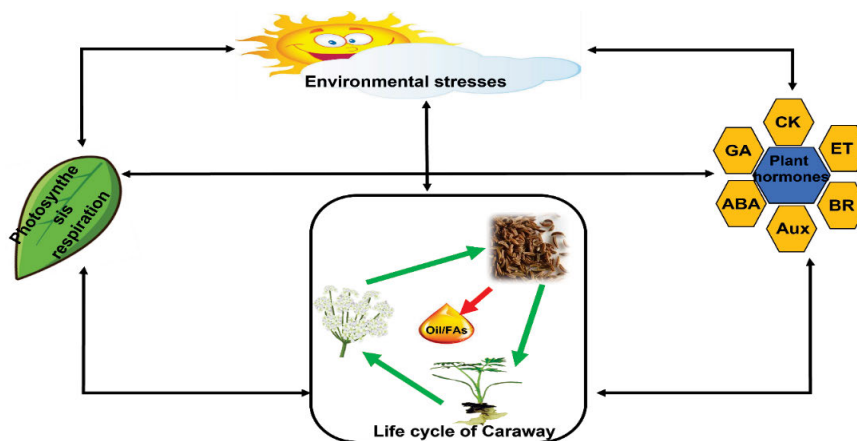


Fig. 5. Seed development and accumulation in caraway seeds and the regulation network; CK = cytokine, GA = gibberellic acid, ABA = abscisic acid, AUX = auxin, BR = brassinosteroid, ET = ethylene; source: own elaboration

CONCLUSIONS

In present study, the effect of different sowing times and plant spacings on the growth, yield, and oil production of caraway plants were investigated. Under semi-arid conditions (Egypt), the findings revealed that seeding caraway plants on the 15th of October with a plant spacing of 25 cm produced the maximum dry weight (72.6 g·plant⁻¹), fresh weight (266.15 g·plant⁻¹), seed yield (37.43 g·plant⁻¹), and oil yield (0.659 cm³·plant⁻¹) and oil yield (0.659 cm³·plant⁻¹). The plants receiving the same treatment had the most umbels (50.83 number per plant) and essential oil (1.78%). Plants seeded on the 15th of November with a spacing of 15 cm, on the other hand, had the lowest values of reported features. While planting caraway plants on the 15th of October with a 15 cm plant spacing yielded the maximum value of plant height (135.35 cm). Finally, the plants sown on 15th October with a maximum plant spacing of 25 cm exhibited the best morphological, biochemical, and yield properties of caraway.

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