Iran Agricultural Research (2023) 42 (2) 84-92.

Shiraz University

Iran Agricultural Research

Journal homepage: https://iar.shirazu.ac.ir

Research Article

Effects of sowing rate on morphological and yield-related traits in camelina: Determination of optimal sowing date

Mohammad Ziaei , Ruhollah Naderi* , Bahram Heidari , Mohsen Edalat

Department of Plant Production and Genetics, School of Agriculture, Shiraz University, Shiraz, I. R. Iran

ARTICLE INFO

Keywords:
Crop production
Low input crop
Oilseed plant

ABSTRACT- Proper timing in planning for sowing dates and optimization of plant density are crucial for maximizing camelina (*Camelina sativa* (L.) Crantz) yields with great potential for enhancing food security and animal feed. This study aimed to evaluate how planting time and density affect camelina seed yield in southern Iran. A two-year field study was performed at Shiraz University, School of Agriculture, Iran, to examine five different sowing dates (10 November, 10 December, 10 January, 10 February, and 10 March) and eight sowing densities (3, 4, 5, 6, 7, 8, 9, and 10 kg ha^{-1}). The results demonstrated significant impacts of sowing date and density on seed yield. This study showed that 10 January and 10 February were optimal sowing dates (687.9 ± 30 and 731.3 ± 40 kg ha^{-1}, respectively), and the highest seed yield was obtained at a sowing density of 6 kg ha^{-1} (686.4 ± 30 kg ha^{-1}). Plant height was influenced by the sowing date, while seed yield and yield components were affected by both the sowing date and density. This research highlights the importance of selecting optimal sowing dates and densities to maximize camelina yield in Fars Province, Iran. Further studies are necessary to investigate how these factors affect different camelina varieties in various regions of Iran, ultimately leading to the development of tailored cultivation practices for optimal yield and sustainability in camelina production.

INTRODUCTION

Oilseed crops can contribute to food security and animal feed in Iran. One such crop, *Camelina sativa* (L.) Crantz, from the Brassicaceae family, has a rich history of cultivation dating back 6,000 years (Anderson et al., 2019). Camelina's unique characteristics, including a short period of growth, minimum input needs, and tolerance to biotic and abiotic stresses, set it apart as a crop with significant agronomic promise in comparison to other oilseed crops (Berti et al., 2016; Kim et al., 2018; Borzoo et al., 2021). Camelina oil contains high polyunsaturated fatty acids, primarily linoleic (C18:2) and linolenic (C18:3) acids. This high unsaturation amount is offset by the relevant level of tocopherol (~800 mg kg^{-1}) (Berti et al., 2016) in a way that camelina oil can be usually stabilized against oxidation, which makes it applicable to be used in numerous markets related to food, feed, and bio-based products (Righini et al., 2016).

Camelina is a versatile crop with applications in biodiesel and cosmetic industries. Recently, there has been growing interest in cultivating camelina as a food product for having bioactive compounds that promote human (Borzoo et al., 2021). In North America and Europe, camelina appears as a viable alternative to soybean and other summer annuals with shorter growing period (Gesch and Archer, 2013; Berti et al., 2015). Despite its potential, camelina has not been extensively studied in Iran due to limited access to genetic material, whereas rapeseed has traditionally received more attention. Camelina can be grown both in spring and winter annually, making it a valuable addition to crop rotation systems (Anderson et al., 2019). Its adaptability to challenging environments makes it a strong competitor to other oilseed crops. Cultivating camelina in dry areas can assist with crop rotation, improve soil nutritional qualities, and promote sustainable agricultural practices (Borzoo et al., 2021).

Contrary to winter rapeseed, camelina has a much shorter life cycle (almost 20 days shorter), which allows it to be double-cropped with short-season summer crops such as soybean, sunflower (*Helianthus annuus* L.), and millet (*Setaria italica* L.). This versatility makes camelina an attractive alternative option for producers. With a growing interest in cultivating new camelina cultivars, there is a pressing need to establish and improve optimal management strategies for camelina production. Camelina has been the subject of extensive researches in the US, Europe, and Canada. Since it has shown adaptability to various climates and soil types, previous studies on camelina sowing dates have led to mixed results. For instance, Urbaniak et al. (2008) found no significant impact of sowing date on seed yield and oil content in eastern Canada. In contrast, Gesch (2014) discovered that seed yields varied from 2300 kg ha^{-1}

* Corresponding author, Associate Professor, Department of Plant Production and Genetics, School of Agriculture, Shiraz University, Shiraz, I. R. Iran.
E-mail address: rnaderi@shirazu.ac.ir
https://doi.org/10.22099/iar.2024.50494.1611
Received 16 June 2024; Received in revised form 25 August 2024; Accepted 27 August 2024
Available online 02 December 2024

to 743 kg ha^{-1}, with the highest yields occurring from sowing dates between mid-April and mid-May in the US.

Establishing an adequate plant stand is vital for crop production. Lower resource-use efficiency and more weed problems can be a result of mismanaged stands, thus causing lower yields. In some environments, it has been reported that camelina plant stand establishment can vary substantially (Gesch, 2014). It has been noticed that this variability is often linked to the fluctuations in temperature and rain around the sowing period. Some studies on sowing density for camelina production showed that yield could vary among a wide range of plant populations, mainly due to the camelina growth plasticity (Urbaniak et al., 2008; McVay and Khan, 2011). Thus, it is essential to select a sowing density that optimizes both productivity and seed costs. Weed management plays a significant role in establishing camelina stands. Moderately high densities of camelina have been reported to be effective in suppressing weed growth (Gesch and Cermak, 2011), which is particularly crucial because of the limited herbicides that camelina can tolerate.

In recent years, water scarcity has become a significant constraint on crop production in Iran. Common oilseed crops like rapeseed, soybean, and sunflower usually demand substantial water inputs. This high water requirement poses a significant challenge, particularly in dry climates inherent to Iran, where drought stress is usually persistent. Consequently, cultivating low-input oilseed crops such as camelina has garnered considerable interest from farmers and researchers (Ahmadvandi et al., 2021). Camelina, known for its drought tolerance and low water requirements, presents a viable alternative to traditional oilseeds in dry environments. Its ability to thrive with minimal water supplies makes it particularly well suited to the harsh climatic conditions of many regions in Iran. Additionally, camelina can adapt to poor soil conditions. Its short growing season further increases its appeal as a suitable crop choice. A shift towards camelina cultivation can also reduce the pressure on water resources, contributing to more sustainable agricultural practices. Researchers are particularly interested in camelina because of its potential to provide a reliable oilseed crop under adverse conditions, and farmers are drawn to its economic viability and lower input costs. Furthermore, camelina is resistant to pests and diseases, which minimizes the need for chemical interventions, aligning with eco-friendly farming practices and reducing environmental impacts (Hazrati et al. 2024).

Since camelina has not been extensively cultivated in Iran, there is little information on its agronomic evaluation or management details, such as sowing date and density, especially in southern Iran where dry conditions prevail. Therefore, the present research was performed to evaluate the impact of camelina sowing dates and densities on its seed yield production and oil content.

MATERIALS AND METHODS

Field site description

A two-year field study was conducted at the Research Field of Shiraz University, School of Agriculture, Iran (2019 and 2020). The coordinates of the study site were 29.73693°N, 52.58225°E, with an elevation of 1,810 meters above sea level. The soil at the site was classified as silty loam (fine, mixed mesic, Typic Calcixerpets). Some of the soil characteristics are given in Table 1. Meteorological data are shown in Table 2.

Table 1. Some characteristics of the studied soil

pH	EC	Total nitrogen content	Available phosphorus content	Available potassium content	Organic matter
8	0.70 dS m^{-1}	0.05%	50 mg kg^{-1}	100 mg kg^{-1}	0.6%

Table 2. Monthly precipitation (mm), mean monthly temperature (◦C) for growing season of 2020-2021 and 2021-2022.

2020-2021 growing season			
Year	**Month**	**Mean precipitation (mm)**	**Mean air temperature (˚C)**
2020	October	38.5	21.1
2020	November	53.5	13.9
2020	December	7	12.2
2021	January	9	16.6
2021	February	47	18.1
2021	March	4	24.9
2021	April	1.5	28.6
2021	May	0	33.8
2021	June	0	36.2
2021	July	1	35.7
2021-2022 growing season			
Year	**Month**	**Mean Precipitation (mm)**	**Mean air temperature (˚C)**
2021	October	5	20.9
2021	November	1.5	18
2021	December	120	11.3
2022	January	17	14.1
2022	February	5	19.5
2022	March	3.5	24.5
2022	April	5	27.6
2022	May	0	35.8
2022	June	0	37
2022	July	45	34.5

Table 3. Seed yield (kg ha^{-1}) affected by seed rate.

Seed rate (kg ha^{-1})	Seed yield
10	606.5b
9	631.3ab
8	629.5ab
7	652.0ab
6	686.4a
5	640.2ab
4	537.1c
3	517.3c

Plant material and cultivation

The experiments were set up in a split plot design based on a randomized complete block with three replicates. The study included five different sowing dates (10 November, 10 December, 10 January, 10 February, and 10 March) and eight sowing densities, i.e., ranging from 3 to 10 kg ha^{-1} (3, 4, 5, 6, 7, 8, 9, and 10 kg ha^{-1}). Both sowing dates and densities were considered as main plots. The camelina seeds used in this study were obtained from the Seed and Plant

Improvement Cooperative (Fars province, Iran). In both years of the study, a camelina cultivar 'Soheil' was used. Prior to the study, the germination rate of the seeds was tested under controlled conditions and found to be greater than 90%. The seeds of "Soheil" camelina had an average 1000-seed weight of 1.1 g.

The preparation of seedbeds was meticulously carried out utilizing a mold-board plow, disk harrow, and leveler in the study field that had been left fallow during the previous growing season. Camelina seeds were sown according to the specific sowing dates and rates treatments. Each plot measured 10 m in length and 3 m in width. The field was irrigated using a sprinkler system immediately after sowing, followed by two additional irrigations every five days, and as needed thereafter. Weeds were removed manually and regularly, thus eliminating the need for chemical herbicides. Urea, containing 46% nitrogen, was used according to the Agricultural Organization of Fars Province (50 kg N ha^{-1}) with half of the fertilizer being used at sowing and the remaining half top-dressed at the stem elongation stage.

Camelina harvesting

One square meter section from the central two rows of each plot was harvested to assess camelina seed yield and its components.

Statistical analysis

Statistical significance among mean values was assessed through an analysis of variance (ANOVA). Upon detecting significant differences, individual treatment means were compared using Duncan's multiple range test ($P < 0.05$). Since no significant interactions ($P > 0.05$) were observed between years and treatments across all measured parameters, data from both years were combined. The statistical analysis was conducted using SAS version 9.1 (2009). To assess the impact of sowing densities on the various response variables measured, quadratic models were utilized for seed yield (Kg ha^{-1}) and number of seeds per silicle, while linear models were used for the number of plants m^{-2}, number of silicle plant^{-1}, number of sub-branches plant^{-1}, and the 1000-seed weight.

RESULTS AND DISCUSION

Sowing date and density significantly affected the number of silicles per main stem (F = 22.73, $P < 0.0001$ and F = 7.78, $P < 0.0001$), number of sub-branches per plant (F = 47.00, $P < 0.0001$ and F = 13.83, $P < 0.0001$), number of plants per m^{-2} (F = 2.34, $P < 0.05$ and F = 18.76, $P < 0.0001$), 1000-seed weight (F = 3.87, $P < 0.0001$ and F = 13.06, $P < 0.0001$), and seed yield (F = 23.70, $P < 0.0001$ and F = 5.58, $P < 0.0001$). Plant height was affected by the sowing date only (F = 57.75, $P < 0.0001$). The interaction between sowing date and sowing density did not significantly affect other parameters ($P > 0.05$).

Effect of sowing date on camelina yield and yield components

The sowing date of 10 January resulted in the highest number of silicles per main stem, showing no significant difference compared to the sowing date of 10 February (Fig. 1D). Additionally, the number of silicles per plant was significantly higher in the plants of 10 January and 10 February sowings, compared to the other dates (Fig. 1D). Although the number of seeds per silicle was the highest in plants of the 10 January sowing, this did not significantly differ from the numbers recorded in plants sown on 10 November, 10 December, and 10 February.

The highest plant density per square meter was recorded in plots planted on 10 February, showing no significant difference compared to those planted on 10 January 10th (Fig. 1B). The 1000-thousand seed weight was slightly greater when planted on 10 November, although this difference was not statistically significant when compared to seeds planted on other dates (Fig. 1F). The maximum seed yield was obtained from planting on 10th February, closely followed by the yield from the 10th January planting. Plant height was greater in plots sown in both February and January (Fig. 1G).

Effect of sowing density on camelina yield and yield components

Maximum seed yield was obtained at a seeding density of 6 kg seed ha^{-1}, but it was not significantly different from 5, 7, 8, and 9 kg seed ha^{-1}. Seed yield at seed sowing densities of 3 and 4 was the lowest. Seed yields at sowing densities of 8 to 10 kg seed ha^{-1} were lower than 5 to 7 kg seed ha^{-1} (Table 3). Variations in some yield parameters with more sowing densities was best described through a linear model (see Fig. 2B, Fig. 2C, Fig. 2D, Fig. 2F, and Table 4). In contrast, for other parameters, a quadratic model was a more suitable fit (see Fig. 2A, Fig. 2E, and Table 4).

Our findings suggested that both 10 February and 10 January are ideal sowing dates for maximizing seed yield. The decrease in seed yield observed for sowing dates on 10 November and 10 December, compared to those on 10 January and 10 February, may be due to the freezing conditions that occurred during the 2-leaf stage of camellia. Furthermore, the reduced yield in plants of the 10 March sowing date could be attributed to the synchronization of seed filling with higher temperatures (Fig. 3). According to Liu et al. (2023), middle sowing dates resulted in higher yields, which can be explained by the lower average maximum temperature (28.3 °C), occurring five days before the pod filling stage, compared to early sowing (33.2 °C) and late sowing (30.9 °C). This suggests that sowing time plays a crucial role in determining seed yield in camellia cultivation.

Variations in weather during the growing season has been identified as the main factor affecting crop growth and yield formation across different sowing dates (Li et al., 2012). In studies on wheat, researchers discovered that variations in weather conditions associated with different sowing dates primarily affected wheat growth before flowering (Ding et al., 2016; Li et al., 2012; Zhou et al., 2020). Surprisingly, no significant relationships between wheat growth and rainfall during any of the growth stages were found (Zhou et al., 2020). It is crucial to align crop phenology with the duration of suitable conditions by carefully selecting optimal sowing dates to maximize yield (Caliskan et al., 2008; Zanon et al., 2016). Gordeyeva et al. (2024) noted that in the steppe zone, a prolonged growing season resulted in higher total temperatures and associated with increased soil moisture, leading to extended leaf activity, enhanced photosynthesis, and increased carbohydrate production. Additionally, Alam et al. (2014) reported that an extended growing period without moisture stress allows for a greater uptake of photosynthetic-active radiation, ultimately leading to heightened tiller production.

Table 4. ANOVA table showing the results of linear and quadratic regression models for measuring the effect of sowing rates on camelina (*Camelina sativa* 'Soheil') Seed yield (kg ha^{-1}), number of plants m^{-2}, number of silicle $plant^{-1}$, number of sub-branches $plant^{-1}$, number of seeds $silicle^{-1}$, and 1000 seed weight

Response variable	Figure	Variable	Estimate	SE	t-value	Pr (>|t|)	
Seed yield	Fig. 2A	Intercept	210.110	87.428	2.403	0.044	*
		Seed rate	-8.726	2.214	-3.941	0.0110	*
		Seed rate^2	125.683	29.124	4.315	0.0076	**
Number of plants m-2	Fig. 2B	Intercept	38.6979	5.3259	7.266	0.000346	***
		Seed rate	16.2582	0.7728	21.039	7.51e-07	***
Number of silicle plant-1	Fig. 2C	Intercept	25.86560	0.27817	92.98	1.04e-10	***
		Seed rate	-0.73798	0.04036	-18.28	1.72e-06	***
Number of sub-branches plant-1	Fig. 2D	Intercept	7.44536	0.08637	86.20	1.64e-10	***
		Seed rate	-0.27929	0.01253	-22.29	5.34e-07	***
Number of seeds silicle-1	Fig. 2E	Intercept	9.07435	0.42203	21.502	4.04e-06	***
		Seed rate	-0.01268	0.01069	-1.186	0.289	
		Seed rate ^2	0.10756	0.14059	0.765	0.479	
1000 seed weight	Fig. 2F	Intercept	0.708095	0.014980	47.270	6.01e-09	***
		Seed rate	-0.020476	0.002174	-9.421	8.13e-05	***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1.

In the current study, the number of silicles per main stem and the number of seeds per square meter were identified as two crucial components that contributed to the increased seed yield associated with sowing dates of 10 February and 10 January. Interestingly, Wittenberg et al. (2020) found that the number of silicles in camelina remained consistent across all four sowing dates. Our study also demonstrated a significant impact of sowing date on the 1000-seed weight, which contrasts with earlier findings by Wittenberg et al. (2020). Similarly, Liu et al. (2023) discovered a notable influence of sowing date on the 100-seed weight of soybean, with early sowings that resulted in the lowest 100-seed weight. They suggested that this outcome proves that high temperatures at the pod-filling stage can adversely affect the 100-seed weight because of increased respiration rates and reduced seed size (Gulluoglu et al., 2018).

Plant height was higher at 10 February (59.63 ± 1.06 cm) and 10 January (57.8 ± 1.28 cm). One possible explanation for the higher seed yields observed at the 10 February and 10 January sowing dates could be attributed to the taller camelina plants during these sowing times. Taller plants have the advantage of being more competitive in receiving light, which helps them outcompete weeds. Weeds are problematic in camelina fields, as they can negatively affect seed yield and quality by competing with camelina for essential resources, such as light, water, and nitrogen. In our study, camelina seed yields ranged from 488 to 731 kg ha^{-1}. Camelina is generally more resistant to shattering compared to rapeseed, but the incidence of shattering can be significantly increased by avian predation. This highlights the importance of managing potential threats to ensure optimal seed yield and quality in camelina cultivation.

Our research findings indicated that increasing the seed sowing density up to 6 kg resulted in a significant increase in seed yield. We also discovered a quadratic curvilinear relationship between seed sowing density and camelina seed yield. Previous studies by Baird et al. (2009), O'Donovan et al. (2012), and Willenborg and Johnson (2013) showed that higher seed sowing densities increased seed yield in lentils (*Lens culinaris* Medik), barley (*Hordeum vulgare* L.), and cow cockle (*Vaccaria hispanica* (Mill.) Rauschert), respectively. These studies identified a curvilinear relationship between yield and seed sowing density. However, Gesch et al. (2018) reported that the seed weight per plant of camelina was affected by the seed sowing density, with a decrease in seed weight per plant observed at higher seed sowing density. This phenomenon can be explained by camelina in compensating for yield at lower planting densities, a trait that becomes more pronounced with reduced plant populations. In contrast, studies by Urbaniak et al. (2008) and Gesch et al. (2017) demonstrated minimal impact of seeding rate on camelina yield. Urbaniak et al. (2008) linked this phenomenon to the increased branching as plant densities decreased, while Gesch et al. (2017) showed that dry matter accumulation and seed yield per plant in spring camelina increased with lower plant density, resulting in an overall unaffected seed yield regardless of seed sowing density.

Our study examined the relationship between seed sowing density and camelina seed yield, revealing a curvilinear pattern that contrasts with previous findings by Isidro-Sánchez et al. (2017) regarding wheat yield response to plant density in a linear pattern. Interestingly, our research also uncovered a strong negative relationship between seed sowing density and the 1000-seed weight (Fig. 2F). This aligns with previous results by O'Donovan et al. (2012) regarding a significant decrease in barley seed weight with increasing seed sowing density. However, studies on oat (*Avena sativa* L.) (May et al., 2009) and lentil (Baird et al., 2009) showed no relationship between seed weight and seed sowing density. Isidro-Sánchez et al. (2017) noted a decline in the 1000-seed weight of durum wheat as the seed sowing density increased. They attributed this reduction to increased seed production per unit area, thus creating a larger sink and ultimately limiting the availability of resources.

A notable decrease in seed yield was observed when the seed sowing density increased from 8 to 10 kg seed ha^{-1}, potentially due to intraspecific competition among camelina plants in higher densities. Research has shown that a higher plant density can increase water usage by plants (Hiltbrunner et al., 2007). In addition, Fang et al. (2010) noted a decrease in soil water content as the seed sowing density increased. A lack of water during the reproductive phase can significantly reduce soybean yields by affecting seed count (Brevedan and Egli, 2003). Insufficient irrigation during seed filling can result in smaller seed size (De-Souza et al., 1997). Furthermore, short periods of stress during flowering and pod formation stages may lead to decreased yields (Vieira et al., 1992). On the other hand, increased water availability reportedly enhanced seed set and seed mass in *Mertensia ciliata* (Gallagher and Campbell, 2021) that highlights the importance of proper water management in optimizing crop yields. However, O'Donovan et al. (2012) found that soil moisture did not cause a restriction, implying that the decrease in yield was not exclusively due to competition for soil water under conditions of high plant densities. In research on maize (*Zea mays* L.), it was found that decreased biomass accumulation under increased plant densities was attributed to competition for available light (Page et al., 2010). A comparable mechanism might elucidate the reduction in barley yield observed at higher seed sowing densities, as observed in previous studies by O'Donovan et al. (2012) and McKenzie et al. (2011). In addition, Iboyi et al. (2024) found that increasing seed sowing densities in *Brassica carinata* led to a decrease in photosynthesis, stomatal conductance, and water use efficiency, particularly during bolting. They suggested that optimizing yield at a seed sowing density of 6 kg seed ha^{-1}, as opposed to 10 and 15 kg seed ha^{-1}, could be attributed to the phenotypic plasticity commonly observed in many Brassica species. This plasticity involves adjustments in vegetative growth, such as increasing lateral branching, pod formation, and leaf area, to compensate for decreased plant density.

A clear relationship was discovered between seed sowing densities and the number of established camelina plants per square meter. This relationship confirms previous findings on various crops, such as camelina (Urbaniak et al., 2008; Pashtetskiy et al. 2021), barley (McKenzie et al., 2005; O'Donovan et al., 2012), oat (May et al., 2009), and lentils (Baird et al., 2009), where a positive association between seed sowing density and plant density was observed. Seed sowing densities of 8-10 kg seed ha^{-1} resulted in higher seed yields and plants per square meter compared to other seed sowing densities. However, the 1000-seed weight in these treatments was lower in comparison.

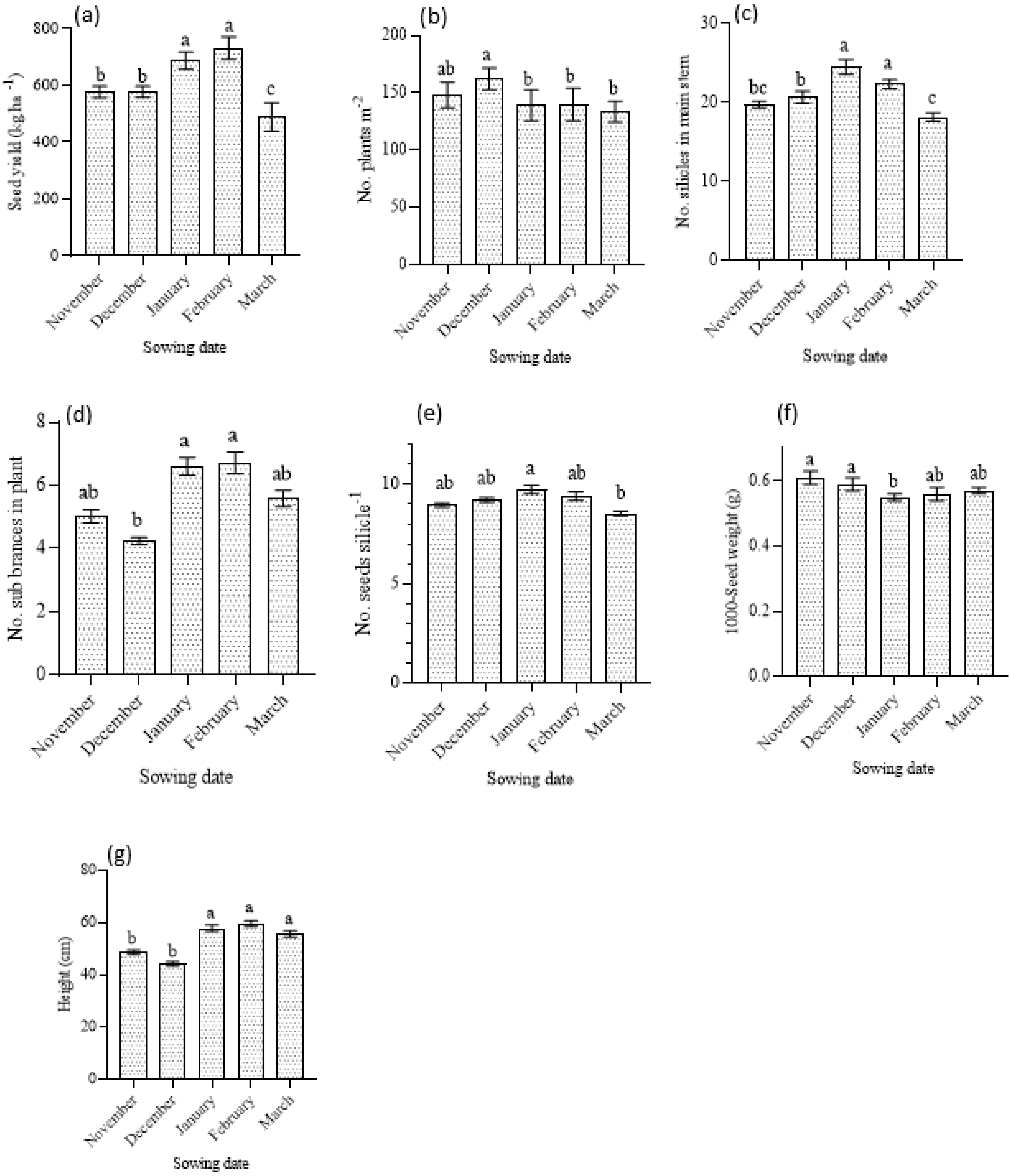

Fig. 1. Effect of seeding dates on camelina ('Soheil') yield and yield components (a: Seed yield, b: number of plants m^{-2}, c: number of silicle $plant^{-1}$, d: number of sub branches $plant^{-1}$, e: number of seeds $silicle^{-1}$, f: 1000 seed weight, and g: height). Data were aggregated across both years.

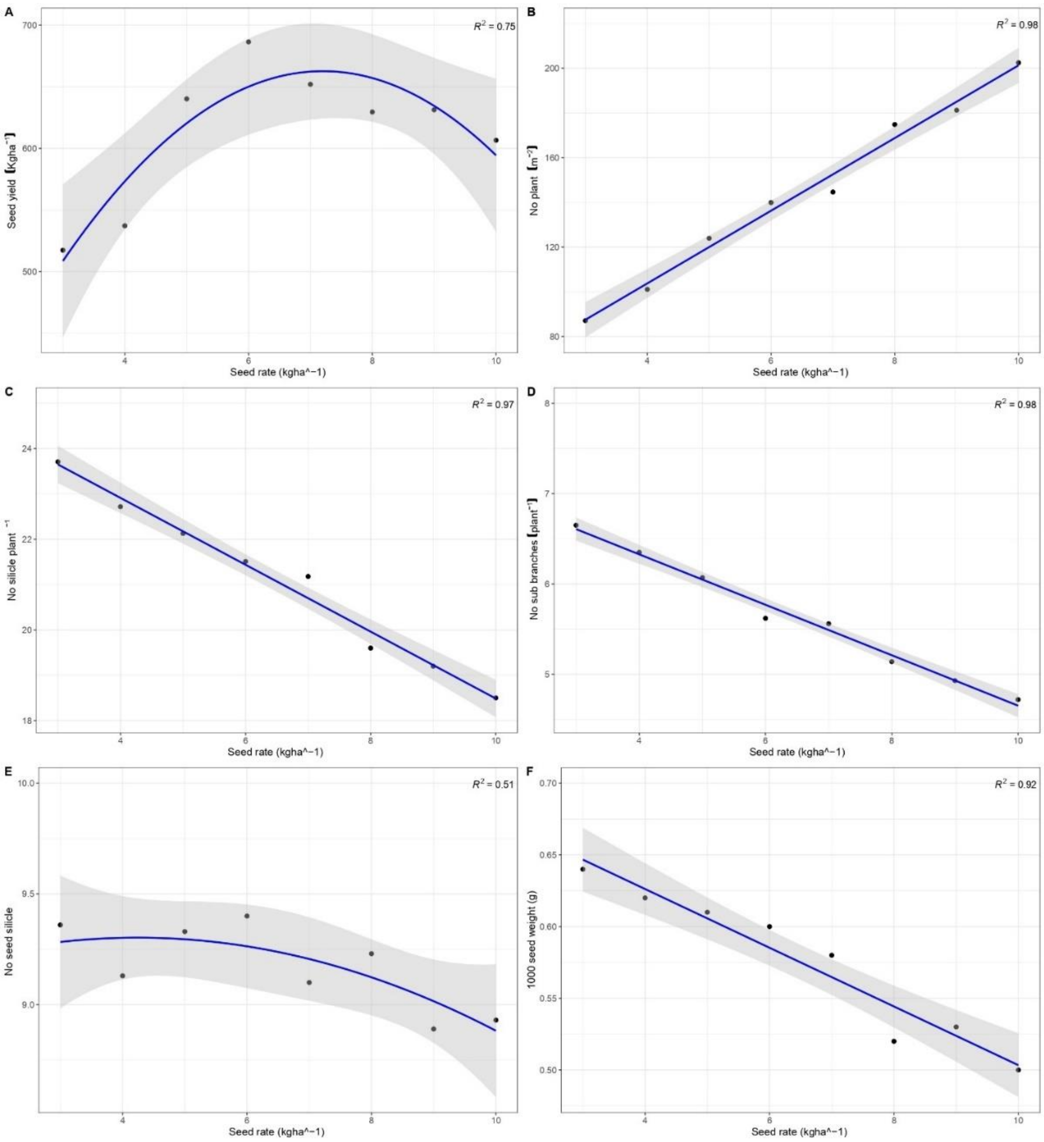

Fig. 2. Effect of seed sowing density on camelina ('Soheil') yield and yield parameter (A: seed yield, B: number of plants m^{-2}, C: number of silicle $plant^{-1}$, D: number of sub branches $plant^{-1}$, E: number of seeds $silicle^{-1}$, and F: 1000-seed weight). Data were aggregated across both years. Blue lines indicated the best fit using linear or quadratic models, while grey shadings represent 95% confidence intervals around the fit.

CONCLUSION

The current study focused on determining the optimum sowing date and seed sowing densities for camelina cultivation in Fars Province, Iran. Our findings revealed that maximum seed yield was achieved when sowing was set on 10 January and 10 February. A seed sowing density of 6 kg ha^{-1} resulted in higher camelina seed yields. In general, our research suggests that sowing on 10 January and 10 February, along with a seed sowing density of 6 kg ha^{-1}, are the most effective practices for maximizing camelina yields in Fars Province, Iran. Further studies are necessary to explore the impact of sowing date and seed sowing density on different varieties of camelina in various regions of Iran.

FUNDING

This research was funded by Shiraz University, grant number GCB4M154663.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Conceptualization, Ruhollah Naderi. and Mohammad Ziaei; methodology, Mohammad Ziaei; formal analysis, Ruhollah Naderi, Bahram Heidari; investigation, Mohammad Ziaei; writing—original draft preparation, Mohammad Ziaei, Ruhollah Naderi.; writing—review and editing, Mohammad Ziaei, Ruhollah Naderi. Bahram Heidari. Mohsen Edalat; supervision, Ruhollah Naderi. project administration, Ruhollah Naderi; funding acquisition, Ruhollah Naderi.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

ETHICAL STATEMENT

This work is not related to experimental animals or specific human diseases that requires publication and approval of publication ethics.

DATA AVAILABILITY

The authors declare that the datasets are available from the corresponding author on request.

ACKNOWLEDGMENTS

This research was funded by Shiraz University.

REFERENCES

Ahmadvandi, H., Zeinodini, A., Ghobadi, R., Gore, M. (2021). Benefits of adding camelina to rainfed crop rotation in Iran: A crop with high drought tolerance. *Agrotechniques in Industrial Crops*, *1*(2), 91-96. https://doi.org/10.22126/atic.2021.6410.1007

Alam, M. Z., Bell, R. W., Biswas, W. K., & Aditya, T. L. (2014). Response of wheat to sowing date and fertilizer management in Bangladesh. *Field Crops Research*, *163*, 1–13. https://doi.org/10.1016%2Fj.sjbs.2021.06.074

Anderson, J., Wall, N., King, L., Van Sanford, J., Ashley, R., Miller, D., & Boerma, R. (2019). Agronomic evaluation of camelina genotypes in the southeastern United States. *Agronomy Journal*, *110*(1), 1–8. https://doi.org/10.3390/agronomy10121929

Baird, J., Mundel, H. H., & Schmitthenner, A. F. (2009). Seed yield and yield components of lentil as influenced by row spacing, seed rate, and cultivar. *Canadian Journal of Plant Science*, *89*(4), 755–763. https://doi.org/10.59797/ija.v50i4.5135

Berti, M. T., Wilckens, M., Martínez, H. P., & Fischer, J. (2015). Agronomic performance of camelina in the northern Great Plains. *Industrial Crops and Products*, *65*, 321–327. https://doi.org/10.1016/j.indcrop.2017.06.022

Berti, M., Gesch, H., & Eynck, J. (2016). Camelina. In J. Vollmann & I. Rajcan (Eds.), *Oil Crops* (pp:1-30). New York: Springer.

Borzoo, S., Mohsenzadeh, S., & Kahrizi, D. (2021). Water-deficit stress and genotype variation induced alteration in seed characteristics of *Camelina sativa*. *Rhizosphere*, *20*, 100427. https://doi.org/10.1016/j.rhisph.2021.100427

Brevedan, R. E., & Egli, D. B. (2003). Short periods of water stress during seed filling, leaf senescence, and yield of soybean. *Crop Science*, *43*(6), 2083–2088. https://doi.org/10.2135/cropsci2003.2083

Caliskan, S., Caliskan, M. E., Arslan, M., et al. (2008). Effects of sowing date and growth duration on growth and yield of groundnut in a Mediterranean-type environment in Turkey. *Field Crops Research*, 105(1-2), 131-140. https://doi.org/10.1016/j.fcr.2007.08.007

De-Souza, P. I., Cordenunsi, B. R., & Oliveira do Nascimento, J. R. (1997). Effects of water stress on the growth, water relations and solute accumulation in two genotypes of sugar cane. *Brazilian Journal of Plant Physiology*, *9*(2), 115–123. https://doi.org/10.3389%2Ffpls.2017.01077

Ding, Y., Wang, X., Liu, H., Du, D., & Wen, D. (2016). Dynamic responses of wheat yield to climate change and technological advancement in Northeast China. *Journal of Integrative Agriculture*, *15*(5), 1136–1148. http://doi.org/dx.doi.org/10.1155/2019/2767018

Fang, Y., Wang, X., Wang, Z., Zhao, X., Wu, H., & Zhang, X. (2010). Effects of seeding rate and planting pattern on soil water and spring wheat yield on the Loess Plateau of China. *Field Crops Research*, *116*(1-2), 49–57. https://doi.org/10.1016/j.agwat.2023.108572

Gallagher, M. K., & Campbell, D. R. (2021). Water availability and plant reproductive allocation. *American Journal of Botany*, *108*(2), 365–374. https://doi.org/10.1111/nph.14602

Gesch, R. W. (2014). Camelina response to seeding date and rate. *Agronomy Journal*, *106*, 191–198. https://doi.org/dx.doi.org/10.2134/agronj2015.0153

Gesch, R. W., & Archer, D. W. (2013). Double cropping camelina with spring wheat and soybean in the northern Corn Belt. *Agronomy Journal*, *105*, 699–706. https://doi.org/dx.doi.org/10.1016/j.indcrop.2012.05.023

Gesch, R. W., & Cermak, S. (2011). Sowing date and tillage effects on fall-seeded camelina in the northern Corn Belt. *Agron Journal*, *103*, 980–987.

Gesch, R. W., Archer, D. W., Oplinger, E. S., & Forcella, F. (2018). Seed yield, yield components, and oil content of winter camelina grown across five locations in North America. *Industrial Crops and Products*, *111*, 440–449. https://doi.org/10.1016/j.indcrop.2018.08.025

Gesch, R. W., Cermak, S. C., & Forcella, F. (2017). Dry matter accumulation and seed yield of spring camelina as influenced by plant density and planting date in the northern Great Plains. *Industrial Crops and Products*, *109*, 87–95. https://doi.org/dx.doi.org/10.1016/j.fcr.2012.02.019

Gesch, R. W., Perrin, R., & Vetch, J. (2017). Camelina seeding rate and planting date effects on stand establishment and seed yield in the northern Great Plains. *Agronomy Journal*, *109*, 1-10. https://doi.org/dx.doi.org/10.1016/j.fcr.2012.02.019

Gordeyeva, E. Y., Semenov, S. M., Belova, N. A., Lebedeva, I. N., & Schindel, M. G. (2024). Duration of phenological phases and productivity of spring wheat in the steppe zone of the Southern Urals. *Russian Journal of Agricultural and Socio-Economic Sciences*, *4*(100), 10–22. https://doi.org/10.1093%2Fjxb%2Ferac144

Gulluoglu, L., Hatipoglu, R., Derya, G., & Zeynep, H. (2018). Investigating the relationship between pod number and seed yield in soybean. *The Journal of Animal and Plant Sciences*, *28*(4), 1024-1030. http://dx.doi.org/10.2135/cropsci2012.11.0663

Hazrati, S., Rostami, N., Mohammadi, H., Ebadi, M. T. (2024). Improving the growth parameters, yield, and oil quality of camelina in rainfed farming due to the combined use of biochar and supplementary irrigation. *Journal of Agriculture and Food Research*, 16, 101160. https://doi.org/10.1016/j.jafr.2024.101160

Hiltbrunner, J., Liedgens, M., Käch, B., & Stamp, P. (2007). Effect of seed rate and sowing date on dry matter and grain yield of common bean grown at different stand densities in a semi-arid environment. *European Journal of Agronomy*, *26*(1), 66–73. http://dx.doi.org/10.47856/ijaast.2021.v08i3.002

Iboyi, E. A., Nwoke, C., & Jones, P. (2024). Impact of seeding rate on the photosynthetic characteristics and growth of *Brassica carinata* L. *Journal of Crop Improvement*, *38*(1), 1–15. http://dx.doi.org/10.1080/15427528.2022.2163950

Isidro-Sánchez, J., Cirilo, A. G., & Miralles, D. J. (2017). Durum wheat yield response to plant density: A linear or curvilinear relationship? *Crop Science,* 57(4), 2114–2123. http://dx.doi.org/10.1016/j.fcr.2018.12.011

Kim, H. K., Saini, A., & Bassil, H. (2018). *Camelina sativa*, a Montana specialty oilseed crop. Proceedings of the 11th Annual Montana Nutrition Conference and the 4th Annual Montana Pulse Crop Symposium. Montana State University Extension.

Li, C. J., Shi, X. X., & Yang, J. C. (2012). The relationships between sowing date, weather factors and spring wheat yield in the North China Plain: A modeling approach. *European Journal of Agronomy*, *43*, 90–98. http://dx.doi.org/10.17957/IJAB/15.0459

Liu, C., Xu, Y., Zhao, J., Nie, J., Jiang, Y., Shang, M., Zang, H., Yang, Y., Brown, R. W., & Zeng, Z. (2023). Optimizing sowing date and plant density improve peanut yield by mitigating heat and chilling stress. *Agronomy Journal*, *115*(2), Article e21307. https://doi.org/10.1002/agj2.21307

May, W. E., Lafond, G. P., & Holzapfel, C. B. (2009). Seeding rate effects on oat yield and yield components. *Canadian Journal of Plant Science*, *89*(2), 287–295. http://dx.doi.org/10.4141/CJPS-2014-439

McKenzie, R. H., Cavers, P. B., & Lafond, G. P. (2005). Seeding rate effects on barley yield, yield components, and quality in southern Saskatchewan. *Canadian Journal of Plant Science*, *85*(1), 103-108. http://dx.doi.org/10.4141/P04-152

McVay, K. A., & Khan, B. A. (2011). Optimal seeding rate, planting date, and row spacing for camelina in the Northern Great Plains. *Industrial Crops and Products*, 33(3), 605-608. http://dx.doi.org/10.1016/j.indcrop.2010.12.008

O'Donovan, J. T., Harker, K. N., Clayton, G. W., Hall, L. M., & McKenzie, R. H. (2012). Influence of seeding rate, seeding date, and location on the agronomic performance of barley. *Canadian Journal of Plant Science*, *92*(3), 501-509. http://dx.doi.org/10.4141/P02-073

Page, E. R., Tollenaar, M., Lee, E. A., Lukens, L., & Swanton, C. J. (2010). Timing, effect, and recovery from intraspecific competition in maize. *Agronomy Journal*, *102*, 1007–1013. https://doi.org/10.2134/agronj2009.0397

Pashtetskiy, V. S., Turina, E. L., Turin, E. N., Cherkashyna, A. V., & Rostova, Y. N. (2021). Formation of agrocenosis *Camelina sylvestris* in the conditions of the Black Sea region. *IOP Conference Series: Earth and Environmental Science*, *640*, 062018. https://doi.org/10.1088/1755-1315/640/6/062018

Righini, D., Zanetti, F., Martínez-Force, E., Mandrioli, M., Toschi, T. G., & Monti, A. (2019). Shifting sowing of camelina from spring to autumn enhances the oil quality for bio-based applications in response to temperature and seed carbon stock. *Industrial Crops and Products*, *137*, https://doi.org/10.1016/j.indcrop.2019.05.009

Urbaniak, S. D., Caldwell, C. D., Zheljazkov, V. D., Lada, R., & Luan, L. (2008). The effect of seeding rate, seeding date, and seeder type on the performance of *Camelina sativa* L. in the Maritime Provinces of Canada. *Canadian Journal of Plant Science*, *88*(3), 501–508. https://doi.org/10.4141/CJPS07148

Vieira, E. A., Corrêa, L. A., Moreira, M. A., & Paciullo, D. S. (1992). Water stress and soybean productivity. *Scientia Agricola*, *49*(2), 221–230.

Willenborg, C. J., & Johnson, E. N. (2013) Influence of seeding date and seeding rate on cow cockle, a new medicinal and industrial crop. *Industrial Crops and Products*, *49*, 554-560. *https://doi.org/*10.1016/j.indcrop.2013.05.028.

Wittenberg, A., Anderson, J. V., & Berti, M. T. (2020). Crop growth and productivity of winter camelina in response to sowing date in the northwestern Corn Belt of the USA. *Industrial Crops and Products*, *158*, 113036. https://doi.org/10.1016/j.indcrop.2020.113036

Zanon, A. J., Streck, N. A., Grassini, (2016). Climate and management factors influence soybean yield potential in a subtropical environment. *Agronomy Journal*, 108(4), 1447-1454. https://doi.org/10.2134/agronj2015.0535

Zhou, G., Gaiser, T., & Zuo, Q. (2020). Influence of weather conditions on growth and yield formation of a new oilseed crop: A case study on *Camelina sativa* under different climate conditions. *Agronomy*, *10*(1), 123. https://doi.org/10.3390/agronomy10010123.