

Effect of tillage and seeding density on *Camelina sativa* (L.) Crantz under a semi-arid climate

Efecto de la labranza y la densidad de siembra sobre *Camelina sativa* (L.) Crantz bajo un clima semiárido

Efeito do preparo do solo e da densidade de sementeira em *Camelina sativa* (L.) Crantz sob clima semiárido

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Crop production

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Abstract

The Mediterranean Basin is warming at a rate approximately 20 % faster than the global average. In the southern Mediterranean countries, there is an urgent need to identify and adopt alternative crops that combine profitability with adaptability for local farmers. *Camelina* (*Camelina sativa*) has been proposed as a candidate for diversification. However, its agronomic performance under local semi-arid conditions remains poorly understood. To address this gap, a field study was conducted in the Setif region of Algeria over two growing seasons, examining the effects of three tillage systems (conventional tillage, minimum tillage, and direct seeding) and two seeding rates (600 and 800 seeds.m²). Results showed that tillage significantly impacted plant stand establishment, with the highest seedling emergence (436.28 plants.m⁻²) and final plant density at harvest (332.22 plants.m⁻²) obtained under conventional tillage. Seed yield was similar between conventional (120.74 g.m⁻²) and minimum tillage (106.94 g.m⁻²), and both systems significantly outperformed direct seeding (72.35 g.m⁻²). The growing season was identified as the predominant factor influencing the fatty acid composition of camelina oil, with α -linolenic acid ranging from 30.94 % to 35.22 % and oleic acid from 14.33 % to 18.82 %. These findings demonstrate that camelina is a resilient and promising oilseed crop capable of diversifying and strengthening agricultural systems in Algeria and similar semi-arid regions.

Resumen

La cuenca mediterránea se está calentando aproximadamente un 20 % más rápido que el promedio mundial. En los países del sur del Mediterráneo, existe una necesidad urgente de identificar y adoptar cultivos alternativos que combinen rentabilidad con adaptabilidad para los agricultores locales. La camelina (*Camelina sativa*) se ha propuesto como un candidato para la diversificación. Sin embargo, su rendimiento agronómico en condiciones locales semiáridas sigue siendo poco comprendido. Para abordar esta brecha, se llevó a cabo un estudio de campo en la región de Sétif en Argelia durante dos temporadas agrícolas, examinando los efectos de tres sistemas de labranza (labranza convencional, labranza mínima y siembra directa) y dos densidades de siembra (600 y 800 semillas.m⁻²). Los resultados mostraron que la labranza tuvo un efecto significativo en el establecimiento de las plantas, con la mayor emergencia de plántulas (436,28 plantas.m⁻²) y la densidad final de plantas a la cosecha (332,22 plantas.m⁻²) obtenidas bajo labranza convencional. El rendimiento de semilla fue similar entre el laboreo convencional (120,74 g.m⁻²) y el laboreo mínimo (106,94 g.m⁻²), y ambos sistemas superaron significativamente a la siembra directa (72,35 g.m⁻²). La temporada agrícola se identificó como el factor predominante que influye en la composición de ácidos grasos del aceite de camelina, con ácido α -linolénico que varió entre 30,94 % y 35,22 % y ácido oleico entre 14,33 % y 18,82 %. Estos hallazgos demuestran que la camelina es un cultivo oleaginoso resistente y prometedor capaz de diversificar y fortalecer los sistemas agrícolas en Argelia y en regiones semiáridas similares.

Palabras clave: cultivos oleaginosos, rendimiento en semillas, contenido de aceite, perfil de ácidos grasos, ácido α -linolénico.

Resumo

A bacia do Mediterrâneo está a aquecer aproximadamente 20 % mais rápido do que a média global. Nos países do sul do Mediterrâneo, há uma necessidade urgente de identificar e adotar culturas alternativas que combinem rentabilidade com adaptabilidade para os agricultores locais. A camelina (*Camelina sativa*) foi proposta como candidato à diversificação. No entanto, o seu desempenho agronómico em condições semiáridas locais ainda é pouco compreendido. Para abordar esta lacuna, foi realizado um estudo de campo na região de Sétif, na Argélia, ao longo de duas temporadas agrícolas, examinando os efeitos de três sistemas de lavoura (lavoura convencional, lavoura mínima e sementeira direta) e de duas densidades de sementeira (600 e 800 sementes.m⁻²). Os resultados mostraram que a lavoura teve um efeito significativo no estabelecimento das plantas, com a maior emergência de plântulas (436,28 plantas.m⁻²) e a densidade final de plantas na colheita (332,22 plantas.m⁻²) obtidas sob lavoura convencional. O rendimento de sementes foi semelhante entre a lavoura convencional (120,74 g.m⁻²) e a lavoura mínima (106,94 g.m⁻²), e ambos os sistemas superaram significativamente a sementeira direta (72,35 g.m⁻²). A temporada agrícola foi identificada como o fator predominante que influencia a composição de ácidos graxos do óleo de camelina, com ácido α -linolénico variando entre 30,94 % e 35,22 % e ácido oleico entre 14,33 % e 18,82 %. Estes resultados demonstram que a camelina é uma cultura oleaginosa resiliente e promissora, capaz de diversificar e reforçar os sistemas agrícolas na Argélia e em regiões semiáridas semelhantes.

Palavras-chave: culturas oleaginosas, rendimento em sementes, teor de óleo, perfil de ácidos graxos, ácido α -linolénico.

Introduction

Camelina (*Camelina sativa* (L.) Crantz) is an ancient oilseed crop of the Brassicaceae family that has gained worldwide attention due to its favorable agronomic traits and its potential for industrial and nutritional applications (Berti *et al.*, 2016). Primarily cultivated for its oil, camelina seeds contain approximately 30 to 48 % of oil by weight (Guendouz *et al.*, 2022). This oil is rich in polyunsaturated fatty acids, comprising about 36-41 % alpha-linolenic acid (omega-3) and 16-20 % linoleic acid (omega-6) (Tulkubayeva and Vasin, 2018). Additionally, camelina oil contains considerable amounts of tocopherols (558-761 mg.kg⁻¹) and phytosterols (3310-4420 mg.kg⁻¹) (Ratusz *et al.*, 2018).

The Mediterranean Basin is recognized as one of the regions most vulnerable to climate change (Lionello and Scarascia, 2018). This vulnerability is especially acute in the southern Mediterranean, where more than 90 % of the cultivated land depends on rain-fed agriculture (Malek and Verburg, 2017). Climate change has already caused notable negative impacts in the region, such as declining crop productivity, soil deterioration, and greater exposure to extreme weather conditions (Lange, 2019). These factors pose serious challenges to agricultural sustainability and food security.

Research across diverse geographic regions reveals that the effects of tillage on camelina vary widely, depending on environmental conditions. In a Greek study, equivalent yields were reported between conventional and minimum tillage systems, although conventional tillage consistently produced higher protein content in seeds (Angelopoulou *et al.*, 2023). In contrast, in the northern Corn Belt, U.S., higher yields were observed under no-till systems (Gesch and Cermak, 2011). These differences are likely related to variations in rainfall, suggesting that the benefits of a tillage system may depend on soil moisture: no-till may perform better in wetter areas, while conventional tillage could provide an advantage in very dry conditions by enhancing water infiltration. Sowing density effects revealed substantial phenotypic plasticity, with plants compensating for low density through increased branching, whereas increasing plant density from 200 to 400 plants.m⁻² was reported to reduce protein content (Bobrecka-Jamro, 2018). Across wide density ranges (113-2905 plants.m⁻²), plant density was strongly correlated with both biomass (R² = 0.85) and seed production (R² = 0.87) (Bakhshandeh *et al.*, 2023).

Camelina is successfully cultivated in multiple countries across Europe (Germany, France, Italy, and Slovenia), North America (United States and Canada), and parts of Asia (Kazakhstan and China), and has demonstrated adaptability to diverse climatic conditions. Given its agronomic potential and nutritional value, could camelina be successfully grown under the local conditions of Algeria?

This study was conducted within the framework of the 4CE-MED project and aimed to (1) evaluate the agronomic performance of camelina (*C. sativa*) under a semi-arid climate, (2) assess oil quality in response to different crop management practices, and (3) provide recommendations for camelina cultivation based on the study findings.

Materials and methods

Site description

Camelina was sown during the 2021/2022 and 2022/2023 growing seasons at the National Agricultural Research Institute, Setif Unit (36°09' N, 5°22' E; 968 m.a.s.l.) under rainfed conditions. The soil at the experimental site was classified as clay loam (24.34 % sand,

43.18 % silt, and 32.48 % clay) using the Robinson pipette method as described by Mathieu and Pieltain (1998). Organic matter (1.81 %) and total nitrogen (0.08 %) were determined according to Mathieu and Pieltain (2003). The soil had an alkaline pH of 8.56 and an electrical conductivity of 156 $\mu\text{S}\cdot\text{cm}^{-1}$, indicating non-saline conditions according to FAO thresholds (Food and Agriculture Organization of the United Nations [FAO], 1988). The high total limestone content of 39.21 % can limit the assimilation of micronutrients by plants. Exchangeable potassium in the soil was 245 $\text{mg}\cdot\text{kg}^{-1}$, indicating adequate potassium availability for plant growth.

The daily precipitation and air temperature throughout the growing cycles were collected from the NASA website (<https://power.larc.nasa.gov/data-access-viewer/>) and presented in figure 1. The blue reference line at 4 °C represents the base temperature for camelina growth, below which plant activity and development become negligible (Gesch and Cermak, 2011). Camelina experienced 16 days of minimal growth in the 2021/2022 season, compared with 24 days in the 2022/2023 season, although the mean temperatures were similar in both seasons (10.03 and 10.06 °C, respectively). Interannual rainfall decreased from 258.87 mm to 239.18 mm, and the precipitation distribution was more irregular during the second season. Notably, a prolonged drought occurred from mid-March to early May, with April recording only 6 mm of rainfall. The filling and ripening stages of the second season were characterized by higher rainfall and cooler temperatures.

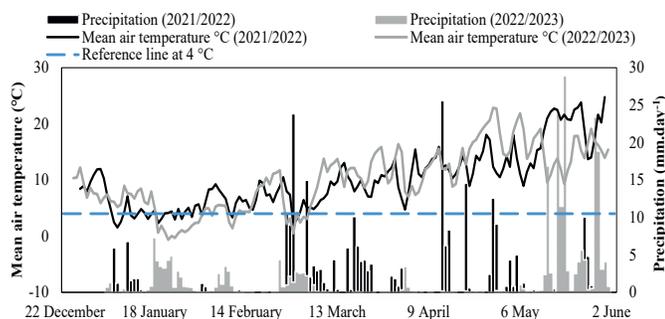


Figure 1. Mean daily air temperature and precipitation.

Experimental design and soil preparation

The experiment was conducted using a split-plot design, arranged in a randomized layout with four replications over two years (2021-2022 as S1 and 2022-2023 as S2). The main plots consisted of three tillage treatments: conventional tillage (CT), minimum tillage (MT), and direct seeding (DS). Subplots consisted of two sowing densities: D1 (600 seeds. m^{-2}) and D2 (800 seeds. m^{-2}). The main plot and subplot sizes were 130 m^2 (20 m \times 6.5 m) and 60 m^2 (20 m \times 3 m).

The direct seeding plots were directly sown without any previous soil preparation. The conventional tillage treatment included moldboard plowing to a depth of 25 cm, followed by two disc harrow passes to break soil clods and incorporate residues, and a final levelling with a spring-tine harrow (APV 1200 M1). In contrast, the minimum tillage system was restricted to a single disc harrow pass followed by a spring-tine harrow pass to achieve a uniform soil surface for sowing. The cultivar *Alba*, provided by Camelina Company España (CCE) in the framework of the 4CE-MED project, was selected for its drought tolerance and compatibility with crop rotations (Stefanoni *et al.*, 2020). Seeds with 97.25 % germination viability were sown at a depth of 1 cm after durum wheat (*Triticum durum* Desf.) as the preceding crop, on 25 December 2021 and 27 December 2022. At sowing, 0.6 kg of monoammonium phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$; 12 % N,

52 % P_2O_5) was applied per subplot (20 m \times 3 m) using a seed drill. Glyphosate was applied at a volume of 18 mL per subplot before sowing to control weeds in the direct sowing plots only.

Plant sampling and measurements

Two counting stations, each spanning 1 meter along a row, were randomly placed within each subplot to evaluate seedling emergence and final plant population density. The harvest dates were May 31, 2022, and June 1, 2023. Five camelina plants were randomly selected from each plot for the computation of branches and capsules. To determine seed yield, plants were manually harvested from a 1 m^2 area, placed in labelled paper bags, and dried at 45 °C for 72 h. The plants were then threshed, and the seeds were cleaned and weighed. Cold-pressed oil was extracted from 200 g of cleaned and dried camelina seeds using an electric oil press machine (Morelian, China) equipped with an 820 W motor and an intelligent digital temperature control system (40-240 °C). The extraction was performed in cold-press mode at a controlled temperature of 45 °C. The extracted oil was weighed, and the oil content was calculated using the following equation:

$$\text{Oil Content \%} = \frac{\text{Weight of extracted oil (g)}}{\text{Weight of seed sample (g)}} \times 100$$

For each treatment, three independent samples of camelina oil were analyzed to determine their fatty acid profile. The transesterification reaction was carried out using 0.1 g of oil dissolved in 2 mL of heptane and 0.2 mL of 2 N methanolic KOH. The fatty acid methyl esters (FAMES) were analyzed using a GC-MS TQ8040 NX system (Shimadzu Scientific Instruments, Kyoto, Japan). A 1 μL sample was injected into the gas chromatograph (GC) operating at 122.5 kPa. Separation was achieved on an Rxi-5Sil MS capillary column (30 m \times 0.25 mm internal diameter, 0.25 μm film thickness), with helium as the carrier gas. The oven temperature was programmed at 40, 170, 180, and 250 °C. The components were identified using the NIST17 library (U.S. National Institute of Standards and Technology), and their relative proportions were calculated as percentages of the total peak area.

Statistical analysis

All data collected in the current study were first tested for normality using the Ryan-Joiner test and showed a normal distribution of residuals. Levene's test was used to evaluate the homogeneity of variances, after which a three-way ANOVA was conducted to test the effects of tillage (T), sowing dose (D), and growing season (S), as well as their interactions, on the measured parameters. The three factors were set as fixed factors and the replication as a random factor. Mean comparisons were conducted using Tukey's pairwise test at a significance level of 0.05. All statistical analyses were conducted using Minitab 22.

Results and discussion

Plant density

For Brassicaceae, plant stand establishment is a fundamental factor that is consistently associated with crop productivity (McVay and Khan, 2011). In the current study, camelina seedling emergence was significantly affected by tillage and seeding rate (table 1). Among the tillage methods used, conventional tillage (CT) produced the highest plant stand, followed by minimum tillage (MT), whereas direct seeding (DS) resulted in the lowest emergence rate (table 1). These differences are likely due to both soil physical properties and seed characteristics. The small size of camelina seeds, typically

ranging from 1.99 to 2.04 mm in length (Ropelewska and Jankowski, 2020), makes them particularly vulnerable to fluctuations in soil moisture and temperature. Benvenuti and Mazzoncini (2018) confirmed this sensitivity and demonstrated that soil compaction strongly inhibits seed germination, with the effect being inversely proportional to seed size. Increasing the seeding rate from 600 to 800 seeds.m⁻², improved seedling emergence from approximately 335 to 411 plants.m⁻², with no significant difference between seasons, likely due to similar favorable sowing conditions. In the 2021/2022 season, 3 mm of rainfall occurred shortly after sowing, with soil temperature averaging 6 °C one week after sowing. In the 2022/2023 season, 2.03 mm of rainfall was recorded eight days after sowing, with an average soil temperature of 5.06 °C. These conditions likely contributed to uniform and successful seedling emergence in both years.

Table 1. Stand establishment, morphological and agronomic parameters, and P value of camelina in relation to tillage, sowing dose, and growing season.

Treatments	SE	SH	NB/p	NC/p	SY	OC	
Tillage (T)	<0.001	<0.001	0.001	0.010	<0.001	0.580	
Dose (D)	<0.001	<0.001	0.318	0.347	0.893	0.693	
Season (S)	0.081	<0.001	<0.001	<0.001	<0.001	<0.001	
T x D	0.501	0.363	0.647	0.422	0.894	0.992	
T x S	0.359	0.142	0.264	0.384	0.829	0.930	
S x D	0.210	0.818	0.212	0.950	0.939	0.346	
T x D x S	0.482	0.390	0.404	0.957	0.896	0.902	
Unit	plants.m ⁻²	plants.m ⁻²	number	number	g.m ⁻²	%	
Tillage	CT	436.28 ^a	332.22 ^a	8.60 ^a	185.48 ^a	120.74 ^a	30.33 ^a
	MT	373.08 ^b	268.07 ^b	8.22 ^a	176.22 ^a	106.94 ^a	30.58 ^a
	DS	310.16 ^c	176.90 ^c	7.35 ^b	153.00 ^b	72.35 ^b	30.39 ^a
DOSE	D1	335.04 ^b	235.61 ^b	8.19 ^a	175.55 ^a	99.55 ^a	30.47 ^a
	D2	411.31 ^a	282.51 ^a	7.92 ^a	167.58 ^a	100.47 ^a	30.39 ^a
Season	S1	356.94 ^a	279.72 ^a	8.97 ^a	202.45 ^a	116.97 ^a	29.46 ^b
	S2	389.41 ^a	238.40 ^b	7.15 ^b	140.68 ^b	83.05 ^b	31.40 ^a

Different superscript letters in the same column for each factor (tillage, sowing dose, and season) indicate significant differences at the 0.05 level. SE: stand count at seedling emergence per m², SH: stand count at harvest per m², NB/p: number of branches per plant, NC/p: number of capsules per plant, SY: seed yield, OC: oil content.

Plant stand at harvest was significantly affected by tillage, sowing density, and growing season. Conventional tillage maintained higher plant density until harvest, and the effect of seeding rate persisted; as the seeding rate increased, the final plant counts also increased. In contrast to seedling emergence, the growing season strongly affected the camelina density at harvest ($p < 0.001$). This discrepancy between seedling emergence and plant population at harvest was mainly due to plant mortality, which reached approximately 38.8 % due to the drought prevailing during the 2022/2023 season. According to Tahasin *et al.* (2024), drought poses a considerable threat to total crop failure, particularly in regions where agriculture relies heavily on rainfall rather than irrigation. Camelina is recognized for its drought tolerance and suitability for cultivation in semi-arid regions. However, its vulnerability to prolonged drought remains a concern. For instance, camelina cultivation in Morocco failed after two months without rainfall following germination (Berzuini *et al.*, 2024).

Plant yield and seed quality attributes

The tillage treatments and growing season influenced the number of branches and capsules per plant, as well as the seed yield. In contrast, oil content was affected only by season (table 1). Plants cultivated in tilled soil produced more branches and capsules than those in no-till plots. This difference in branching and capsule

formation was also reflected in seed yield, which was higher in tilled treatments, although no significant difference was observed between conventional and minimum tillage. Studies on the effects of tillage on oilseed crops have yielded conflicting findings. Some authors reported lower yields under conventional tillage (Jankowski *et al.*, 2024; Seddaiu *et al.*, 2016), while others reported higher yields (Cheřan *et al.*, 2022; Gawęda and Haliniarz, 2022). Collectively, this research suggests that the interaction between tillage systems and environmental conditions is more critical than the tillage method alone. Regarding yield performance under direct seeding, multi-year studies have shown that direct seeding requires a transition period to reach its full benefits, with initial yield decreases followed by long-term improvements. McGregor *et al.* (1999) found that conventional tillage generated greater yields in the early years, but after 14 years, zero tillage surpassed conventional tillage yields by approximately 0.8 t.ha⁻¹.

The drought during the vegetative stage of the 2022/2023 season reduced camelina population density and affected its morphological characteristics, consequently lowering seed yield and its components. Despite the precipitation at the end of the 2022/2023 season, the drought had already limited branching and floral site formation, and camelina failed to compensate for capsule production. This critical period, spanning from 11 March to 28 April 2023, was characterized by a severe water deficit with total rainfall reaching only 5.95 mm, an extended period of 41 days without precipitation, and a mean air temperature of 13 °C. The severity of drought is a fundamental factor guiding plant survival strategies. Drought stress in camelina limits its developmental progress, yielding shorter plants with reduced branching patterns. Waraich *et al.* (2017) also documented yield losses, illustrated by a decline in branch and capsule number per plant. Regardless of middle-season stress, the seed filling and maturation period in the 2022/2023 season shifted towards a cooler period with adequate precipitation, leading to a 6.59 % higher oil content. This confirms that camelina promotes oil biosynthesis when environmental conditions are favorable during late growth stages (Brock *et al.*, 2020; Zanetti *et al.*, 2020).

Within the tested range of 600 to 800 seeds.m⁻², the sowing rate had no significant effect on the number of branches and capsules per plant. McVay and Khan (2011) recommend a seeding rate of 3.4 to 5.6 kg.ha⁻¹ under dry conditions, which corresponds approximately to 400-600 seeds.m⁻². It appears that exceeding the ideal planting density does not provide additional yield benefits. These findings clarify why yields did not increase at higher seeding rates ($p > 0.05$).

Fatty acid composition

Tillage practices and seeding rate did not significantly affect the fatty acid composition of camelina oil (table 2). Previous studies have only found erucic acid (C22:1) and eicosenoic acid (C20:1) to be influenced by tillage (Angelopoulou *et al.*, 2023; Gesch and Cermak, 2011). Research on camelina has demonstrated that genotypic variation, seasonal conditions, sowing time, fertilization, and environmental factors exert the greatest influence on fatty acid composition. The influence of genotype is well-documented, as different varieties exhibit varying fatty acids and responses to growing conditions (Brock *et al.*, 2020; Kurt and Gore, 2020). Obour *et al.* (2017) demonstrated that camelina grown in different locations exhibited distinct oil contents and fatty acid compositions. According to Czarnik *et al.* (2017), planting density affects yield and some seed characteristics, while fertilization regimes primarily influence fatty acid composition.

Table 2. Fatty acid profile (%) and P-value of camelina in relation to tillage, sowing dose, and growing season.

Treatments		α linolenic	Linoleic	Oleic	Eicosenoic	Erucic	Palmitic	Stearic
Tillage (T)		0.463	0.919	0.503	0.270	0.177	0.801	0.379
Dose (D)		0.776	0.550	0.831	0.507	0.259	0.517	0.837
Season (S)		<0.001	0.007	<0.001	0.001	<0.001	0.030	0.036
T x D		0.490	0.781	0.414	0.389	0.716	0.474	0.787
T x S		0.540	0.718	0.893	0.620	0.476	0.938	0.647
S x D		0.634	0.849	0.620	0.641	0.455	0.585	0.346
T x D x S		0.462	0.569	0.636	0.506	0.791	0.927	0.535
Unit		%						
Season	S1	31.66 ^b	21.43 ^a	17.74 ^a	14.34 ^b	2.48 ^b	6.53 ^a	2.01 ^b
	S2	34.45 ^a	20.24 ^b	15.59 ^b	14.98 ^a	2.60 ^a	5.98 ^b	2.49 ^a

Different superscript letters in the same column indicate significant differences at the 0.05 level.

Among the two experimental years, the initial season favored the accumulation of linoleic (omega-6, ω -6), oleic (omega-9, ω -9), and palmitic acids, whereas the second season promoted α -linolenic (omega-3, ω -3), eicosenoic, erucic, and stearic acids. The decrease in α -linolenic acid coincided with an increase in linoleic acid. Smith and Lu (2024) showed that temperature affects linoleic and linolenic acids inversely. The ω -3/ ω -6 ratio was 1.48 in the first season and increased to 1.70 in the second. The 2022/2023 season showed a 12.1 % reduction in oleic acid content compared to the 2021/2022 season, probably due to cooler temperatures during the seed filling. The content of the eicosenoic acid was higher in 2022/2023 (14.98 %) compared to 2021/2022 (14.34 %). The erucic acid concentration was lower in the first season than in the second season. The reduction of erucic acid under higher temperatures was also reported by Sametoglu and Önder (2023). The first year had a higher palmitic acid content (6.53 %) than the second year (5.98 %). Conversely, stearic acid had a lower content in the first year (2.01 %) compared to the second year (2.49 %). This opposite trend reflects the metabolic conversion of palmitic acid (C16:0) to stearic acid (C18:0), resulting in an inverse relationship between the two fatty acids.

Conclusion

These results confirm that camelina can be successfully cultivated under semi-arid conditions when appropriate agronomic practices are applied. Analysis of variance (ANOVA) revealed that the impact of tillage was not uniform across all measured parameters; it should be noted that plant density, seedling emergence, branching, capsule number, and seed yield responded significantly. Minimum tillage did not differ significantly from conventional tillage for most traits evaluated. Both treatments produced significantly higher yields than direct sowing. Planting density affected plant establishment but did not significantly influence seed yield, oil content, or quality. Based on the results of this study, minimum tillage combined with a sowing density of 600 seeds.m⁻² appears to be the optimal option for camelina cultivation under the climatic and edaphic conditions of the Setif region. This approach not only ensures yield stability and preserves oil quality, but it also aligns with an economic and ecological strategy by reducing operational costs for local farmers while avoiding the negative environmental impact of intensive tillage. Oil content and fatty acid composition were primarily driven by growing season conditions, and neither tillage nor sowing density had a significant effect, highlighting the strong environmental influence over oil biosynthesis.

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