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Research Article

Optimizing Planting Arrangement and Density for Enhanced Oil Yield and Fatty Acid Composition in a Non-Shattering Sesame Cultivar

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ABSTRACT

Sesame (*Sesamum indicum* L.) is a globally significant oilseed crop valued for its high-quality oil, rich in unsaturated fatty acids and antioxidants, yet its production faces challenges such as low yield, shattering losses, and variable oil quality, particularly in semi-arid regions like Iran where domestic demand necessitates enhanced local cultivation. This study aimed to investigate how row spacing (30, 45, 60 cm) and plant density (5, 8, 11, 14 cm) affect oil yield and fatty acid composition in the non-shattering sesame cultivar. Conducted in 2020 at the Moghan Agricultural Research Station in Northwest Iran, the experiment utilized a strip plot design based on a completely randomized block design with four replications. Treatments combined row spacings and plant densities, with oil content and fatty acid profiles analyzed via gas chromatography, and data evaluated using ANOVA, LSD and regression tests. Results revealed that a row spacing of 45 cm with plant spacings of 8–11 cm (20–28 plants/m²) maximized oil content at 55.45% and optimized fatty acid profiles, particularly increasing linoleic acid (up to 48.31%) while maintaining oleic acid levels (up to 40.85%), with significant RS × PS interactions ($P < 0.01$) highlighting their combined influence. These findings provide practical recommendations for Iranian farmers to enhance sesame oil quality and yield, contributing to sustainable production systems in semi-arid regions and reducing reliance on imported edible oils, while suggesting further multi-year studies to address environmental variability in fatty acid biosynthesis.

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INTRODUCTION

Sesame (*Sesamum indicum* L.), one of humanity's oldest oilseed crops, is globally revered for its high-quality oil, which is rich in unsaturated fatty acids, antioxidants, and lignans (Babu et al., 2024; Langyan et al., 2022). Sesame oil is highly valued for its nutritional and health benefits, primarily due to its fatty acid composition and bioactive compounds. It is rich in unsaturated fatty acids, particularly oleic (omega-9) and linoleic (omega-6) acids, which contribute to cardiovascular health (Gouveia et al., 2017; Oboulbiga et al., 2023). The oil also contains important bioactive compounds such as lignans, tocopherols, and phytosterols, which possess antioxidant properties (Oboulbiga et al., 2023; Wacal et al., 2024). Sesame oil's unique composition makes it valuable for both culinary and industrial applications, particularly where oxidative stability is crucial (Kouighat et al., 2025). Global sesame production has increased substantially over the past 60 years, with Asia and Africa as primary producers (Sanni et al., 2024). Globally, sesame is cultivated on approximately 13 million hectares, yielding around 6 million tons of seeds with an average productivity of 520 kg per hectare. In Iran, the 2023 crop year demonstrated the country's growing influence in the sesame market, with over 42,000 hectares dedicated to sesame cultivation, producing an average yield of 690 kg per hectare and resulting in a total seed yield of 29,000 tons (FAOSTAT, 2023). Iran faces a significant challenge in meeting its domestic demand for edible oils, as the country imports approximately 90% of its required oilseeds and vegetable oils to bridge the gap between production and consumption (Mohammadi et al., 2013). This heavy reliance on imports underscores the urgent need to enhance local cultivation of oilseed crops that are well-suited to Iran's climatic conditions, such as sesame. Sesame, being a drought-tolerant crop, is particularly adapted to regions with water scarcity, making it an ideal candidate for expanding agricultural output in Iran's arid and semi-arid landscapes (Gholamhoseini & Dolatabadian, 2024). Despite its economic importance, sesame production faces challenges such as low yield, shattering losses, and variability in oil quality, necessitating innovative agronomic strategies (Rauf et al., 2024; Yadav et al., 2022). Agronomic practices, including planting arrangement (row spacing) and plant density, are critical determinants of sesame crop performance (Ngala et al., 2013). These factors influence light interception, nutrient uptake, and intra-plant competition, ultimately affecting yield and biochemical profiles (Imo, 2012). Optimal row spacing is essential to maximize light interception, nutrient uptake, and plant population density while minimizing competition among plants, particularly in diverse agroecological conditions. For soybeans, row spacings of 25-51 cm have been shown to maximize seed yield and resource use efficiency (Abeje et al., 2020). In rapeseed, narrow row spacings of 15 cm are recommended to achieve higher seed yields (Ozer, 2003). Similarly, for sesame, row spacings of 30 cm combined with intra-row spacings of 5 cm have been found to optimize seed and oil yields (Öztürk & Şaman, 2012). Investigations in sesame under semi-arid regions have demonstrated that narrower row spacings can enhance yield under rainfed conditions, while wider spacings may benefit irrigated systems by reducing plant stress (Ali et al., 2020). Koocheki et al. (2017) reported that the diamond pattern with 50 plants/m² achieved the highest dry matter and seed yield (1100 g/m²), while the same pattern with 30 plants/m² produced the most seeds (47) and capsules (19.2) per plant. Increasing density from 30 to 50 plants/m² reduced 1000-seed weight by 13% and harvest index from 31% to 28%. The diamond pattern with 50 plants/m² was identified as optimal for sesame cultivation in Mashhad, Iran. In contrast, Habibzadeh and Gholamhoseini (2022) reported no significant difference in sesame yield across various planting patterns. The discrepancy in researchers' findings may be attributed to sesame's differing responses to planting patterns, influenced by cultivar characteristics (especially branching type), planting date, irrigation method, soil fertility, and growing season length (Gholamhoseini et al., 2024). Recent advances in sesame breeding have prioritized non-shattering traits to reduce post-harvest losses (Gebremichael, 2017; Rauf et al., 2024). Sesame breeding programs focus on developing cultivars with minimized shattering to achieve high-yielding and shatter-resistant varieties (Gedifew, 2024). Yet, optimal cultivation practices for these cultivars are poorly defined. Wider row spacing improves photosynthetic efficiency and oil content (El Harfi et al., 2021), light penetration and air circulation, reducing fungal diseases and promoting healthy plant growth. However, excessive spacing may lead to reduced competition, potentially lowering yield due to fewer plants per unit area (Khan & Islam, 2023; Öztürk & Şaman, 2012). Closer spacing may be more beneficial as plants can utilize available water efficiently (Ali et al., 2020; Filimon & Worku, 2018). However, these findings may not extrapolate to modern non-shattering genotypes, which exhibit a modified canopy architecture, with curly and larger leaves, which could alter light interception and canopy density compared to traditional varieties (Teboul et al., 2022; Yol et al., 2021). The fatty acid profile of sesame oil is highly sensitive to environmental and agronomic factors. For example, drought stress elevates oleic acid but reduces linoleic acid (Kim et al., 2006; Tas et al., 2024), while this trend is also observed with increasing

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nitrogen application (Gholamhoseini, 2022; Tas et al., 2024). Row spacing influences the fatty acid profile of sesame oil. Closer row spacing (37.5 cm) was associated with higher contents of eicosenoic acid and saturated fatty acids compared to wider spacing (75 cm) (Bhardwaj et al., 2015). Additionally, row spacing significantly affected oleic and linoleic acid contents, with interactions between row spacing and irrigation also playing a role (Alpaslan et al., 2001). This study explores how row spacing (30, 45, 60 cm) and plant density (5, 8, 11, 14 cm) affect oil yield and fatty acid profiles in a non-shattering sesame cultivar, aiming to fill existing research gaps. It hypothesizes that wider row spacing boosts oil percentage by reducing competition within rows, while a moderate plant density improves fatty acid composition by optimizing light penetration and photosynthetic efficiency. The findings seek to offer practical recommendations for farmers and breeders to enhance sesame oil quality and yield.

MATERIAL AND METHODS

For finding the optimal planting arrangement and density to enhance oil yield and fatty acid composition in a non-shattering sesame cultivar, an experiment was conducted during the 2020 cropping season at the Agricultural Research and Education Center of Ardabil Province, located at the Moghan Agricultural Research Station in the Moghan Plain, Northwest Iran (N39°39', E47°68', sea level= 78 m). The layout of the experiment was as according to a strip plot design based on a completely randomized block design with four replications. For this purpose, the effect of row spacing (30, 45, and 60 cm) was considered as the vertical factor, and the plant spacing within rows (5, 8, 11, and 14 cm) was considered as the horizontal factor. Based on data from the Iran Meteorological Organization (IRIMO, 2021), this area experiences a semi-humid and moderately warm climate. Over the past 30 years, the average annual precipitation has been 251 mm, with most of it occurring in the autumn and early spring. The region experiences a range of precipitation from a minimum of 72.9 mm to a maximum of 523 mm every year. The average annual maximum temperature is 35°C, while the average annual minimum temperature is 8°C. The mean yearly relative humidity stands around 71%. The weather conditions of the experimental site during the sesame growing season in 2020 are presented in Table 1.

Table 1. *Meteorological data for the moghan region during the sesame growing season in 2020*

	July	August	September	October	November
Minimum Temperature (°C)	19.2	21.5	17.9	14.2	7.1
Maximum Temperature (°C)	33.3	32.5	26.8	23.9	18.8
Average Temperature (°C)	27.6	27.0	22.4	19.1	13.0
Precipitation (mm)	0.1	3.9	43.5	29.2	6.2

Physical and chemical properties of the soil at the experimental site are presented in Table 2.

Table 2. *Physical and chemical properties of the soil at the experimental site*

Silt-Clay-Sand (%)	Organic Matter (%)	Nitrogen (%)	Phosphorus (mg/kg)	Potassium (mg/kg)	Salinity (dS/m)	pH
35-42-23	1.35	0.13	10.52	488	0.56	7.95

After land preparation operations in the spring, including plowing, discing, and ridge formation (based on the experimental treatments and by adjusting the distance between ridges), sesame seeds were manually sown at a depth of 1–2 cm in the third decade of June. Based on soil test results, the field soil had a clay-loam texture, pH of 8, salinity of 0.52 dS/m, and 0.11% nitrogen. Additionally, the levels of phosphorus and potassium in the soil were 7.2 mg/kg and 390 mg/kg, respectively. Fertilization was applied according to the local practices in the Moghan region, consisting of 150 kg/ha of urea and 150 kg/ha of phosphate fertilizer, with an additional 50 kg/ha of urea applied as a top-dressing before the flowering stage. Each experimental plot consisted of six planting rows, each 4 meters long. The distance between plots was 1 meter, and the distance between blocks was 2 meters. The non-shattering sesame cultivar (Mohajer) was used, with a germination rate of 98% and purity of 99%. This cultivar, originating from Iran's sesame breeding programs focused on non-shattering traits, was bred using pureline selection methods. The first irrigation was applied immediately after planting,

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with subsequent irrigations performed based on the plant's water needs in a rotational irrigation system. For weed control, 2 liters/ha of the herbicide trifluralin was applied before planting, and manual weeding was conducted during the growing season. To control leaf-eating pests, 250 ml/ha of the insecticide Avaunt was applied in two applications.

Oil content and fatty acid profile analysis

The fatty acid profile of sesame oil was determined using a gas chromatography (Agilent/HP Model 6890) system at the Plant Laboratory of the Research Institute of Forests and Rangelands, Karaj, Iran. First, lipids were extracted from ground sesame seeds using a Soxhlet apparatus with n-hexane as the solvent, followed by drying at 75°C to remove moisture. The extracted oil was then converted into fatty acid methyl esters (FAMEs) through transesterification with methanol and a catalyst (e.g., sodium methoxide or sulfuric acid) at 60–80°C for 30–60 minutes, purified with hexane, and dried with anhydrous sodium sulfate. The FAME sample (1–2 µL) was injected into the GC equipped with a polar capillary column (e.g., DB-23 or BPX-70, 30 m × 0.25 mm × 0.25 µm) and analyzed using a flame ionization detector (FID). The oven temperature was programmed to start at 140°C, ramp at 4–10°C/min to 220–240°C, and hold for 10–15 minutes, with helium as the carrier gas at 1–2 mL/min, injector temperature at 250°C, and detector temperature at 260°C. FAMEs were identified by comparing retention times with known standards, and their percentages were quantified using peak areas relative to the total, processed with software like Agilent ChemStation, ensuring calibration with FAME standards for accuracy and reproducibility.

Data analysis

SAS software (version 9.1) was used to analyze the data after confirming the normality of the experimental data and the homogeneity of variance errors. Furthermore, because of the significant interaction between row spacing and plant spacing, the means comparison for the interaction was conducted using the interaction slicing method combined with the Least Significant Difference (LSD) test, also implemented in SAS. Regression analysis was performed using Excel software, while correlation analysis was conducted using JMP (version 16).

RESULTS AND DISCUSSION

The analysis of variance (ANOVA) demonstrated that row spacing (RS), plant spacing (PS), and their interaction (RS × PS) exerted significant effects on oil content and fatty acid composition in the non-shattering sesame cultivar 'Mohajer' (Table 3). These effects were significant at the 1% probability level ($P < 0.01$) for most traits, with stearic acid showing significance at the 5% level ($P < 0.05$) for RS and PS effects. Block effects were also significant ($P < 0.01$) for oil content, palmitic acid, palmitoleic acid, linoleic acid, α-linolenic acid, and arachidic acid, reflecting spatial variability across experimental units. The low coefficients of variation (CV: 0.007%–4.590%) and minimal error terms indicate high experimental precision and data reliability (Table 3).

Table 3. *Analysis of variance for oil content and fatty acid composition in a non-shattering sesame cultivar*

S.o.V [1]	DF	Oil Content	Palmitic Acid	Palmitoleic Acid	Stearic Acid
B	3	0.077**	0.000**	0.000**	0.018
RS	2	66.140**	0.021**	0.008**	0.123*
Ers	6	0.002	0.000	0.000	0.017
PS	3	8.051**	0.092**	0.002**	0.266**
Eps	9	0.003	0.000	0.000	0.017
RS × PS	6	28.197**	0.101**	0.003**	0.130**
E	18	0.003	0.000	0.000	0.016
CV (%)		0.090	0.030	4.590	2.460

[1]* and ** indicate non-significance and significance at 5% and 1% probability levels, respectively. S.o.V: source of variations; DF: degree of freedom; B: block; RS: row spacing; Ers: error term for row spacing; PS: plant spacing; Eps: error term for plant spacing; RS × PS: row spacing × plant spacing interaction; E: experimental error; CV: coefficient of variations

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Table 3. *Continuation of Table 3*

S.o.V [1]	DF	Oleic Acid	Linoleic Acid	α-Linolenic Acid	Arachidic Acid
B	3	0.002	0.001**	0.001**	0.000**
RS	2	7.695**	17.332**	0.013**	0.003**
Ers	6	0.001	0.000	0.000	0.000
PS	3	2.855**	4.360**	0.034**	0.071**
Eps	9	0.000	0.000	0.000	0.000
RS × PS	6	20.633**	6.861**	0.050**	0.012**
E	18	0.000	0.000	0.000	0.000
CV (%)		0.030	0.007	0.590	0.810

[1]* and ** indicate non-significance and significance at 5% and 1% probability levels, respectively. S.o.V: source of variations; DF: degree of freedom; B: block; RS: row spacing; Ers: error term for row spacing; PS: plant spacing; Eps: error term for plant spacing; RS × PS: row spacing × plant spacing interaction; E: experimental error; CV: coefficient of variations

Oil content

Oil content (OC) was significantly influenced by row spacing, plant spacing, and their resulting plant densities (Table 4), with the highest oil content (55.45%) observed at a row spacing of 45 cm, a plant spacing of 11 cm, and a density of 20 plants/m², compared to the lowest (47.52%) at a row spacing of 60 cm, a plant spacing of 5 cm, and a density of 33 plants/m²; moderate row spacings of 45 cm with plant spacings of 8–11 cm (densities of 20–28 plants/m²) consistently yielded higher oil contents (52.73%–55.45%), likely due to optimized light interception and reduced competition, while wider spacings of 60 cm with 5 cm plant spacing (33 plants/m²) reduced oil content, possibly due to fewer plants per unit area, with the significant RS × PS interaction ($P < 0.01$) underscoring their combined effect; additionally, regression analysis (Figure 1) revealed a quadratic relationship where oil content dipped to ~50% at 30–40 plants/m² before peaking at ~55% at 60–70 plants/m², though the low R^2 (0.0926) indicates that plant density alone explains only 9.26% of the variability, suggesting other factors like environmental conditions or genetics also play key roles.

Table 4. *Mean comparisons of interaction effects for oil content and fatty acid composition in a non-shattering sesame cultivar*

Row Spacing (cm) [1]	Plant Spacing (cm)	Density (P/m²)	Oil Content (%)	Palmitic Acid (%)	Palmitoleic Acid (%)	Stearic Acid (%)	Oleic Acid (%)	Linoleic Acid (%)	α-Linolenic Acid (%)	Arachidic Acid (%)
30	5	67	53.77^{b}	9.074^{a}	0.082^{a}	4.998^{a}	36.15^{d}	47.65^{b}	0.292^{d}	0.505^{a}
	8	42	55.10^{a}	8.872^{b}	0.064^{b}	5.053^{a}	36.21^{c}	48.31^{a}	0.419^{a}	0.458^{b}
	11	30	51.30^{c}	8.728^{c}	0.067^{b}	5.025^{a}	37.24^{b}	47.52^{c}	0.342^{c}	0.342^{d}
	14	24	48.87^{d}	8.619^{d}	0.064^{b}	5.178^{a}	40.31^{a}	46.79^{d}	0.386^{b}	0.427^{c}
45	5	44	52.11^{c}	8.775^{b}	0.173^{a}	5.013^{b}	39.43^{b}	47.70^{b}	0.207^{c}	0.622^{a}
	8	28	52.73^{b}	8.664^{d}	0.099^{c}	5.282^{a}	39.57^{a}	45.11^{d}	0.193^{d}	0.470^{b}
	11	20	55.45^{a}	8.703^{c}	0.106^{b}	5.043^{a}	36.05^{c}	47.73^{a}	0.550^{a}	0.324^{d}
	14	16	55.41^{a}	8.949^{a}	0.089^{d}	5.123^{ab}	36.06^{c}	46.82^{c}	0.269^{b}	0.432^{c}
60	5	33	47.52^{d}	8.769^{c}	0.074^{d}	4.837^{c}	37.84^{c}	47.16^{a}	0.350^{b}	0.503^{a}
	8	21	51.32^{b}	8.867^{a}	0.088^{c}	5.195^{b}	36.84^{d}	46.41^{b}	0.268^{d}	0.474^{b}
	11	15	48.31^{c}	8.556^{d}	0.102^{b}	5.649^{a}	40.85^{a}	43.49^{d}	0.299^{c}	0.431^{c}
	14	12	52.35^{a}	8.824^{b}	0.127^{a}	5.271^{b}	39.67^{b}	45.00^{c}	0.384^{a}	0.364^{d}

[1] Within each trait and treatment, means with the same letter are not significantly different (P>0.05)

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Fatty acid composition

The fatty acid profiles of sesame oil were significantly influenced by row spacing and plant density, with distinct trends observed for saturated, monounsaturated, and polyunsaturated fatty acids (Table 4 and Figure 1).

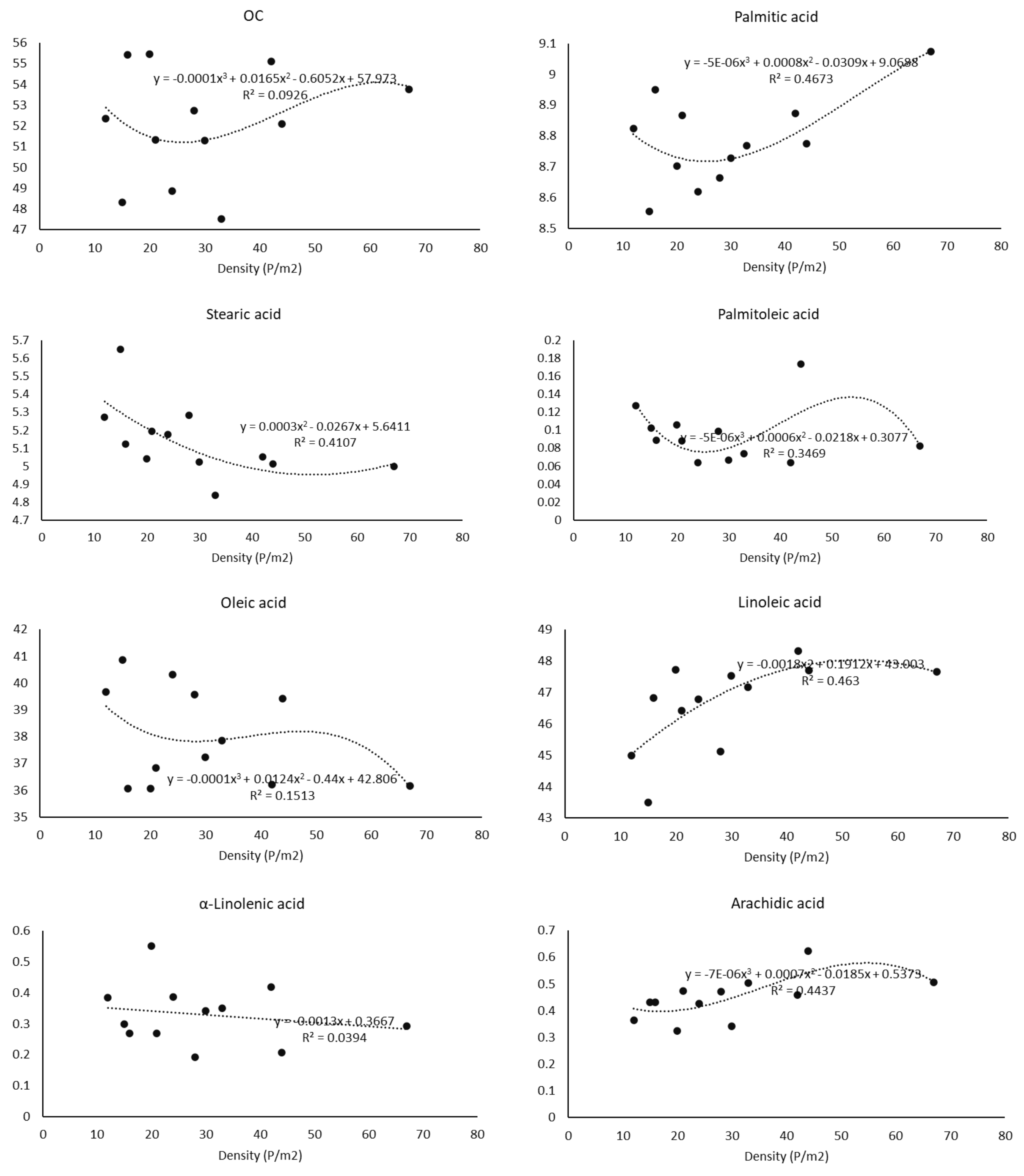

Figure 1. *The effect of different densities on oil content and fatty acid composition in a non-shattering sesame cultivar*

Palmitic Acid (Saturated): Palmitic acid concentrations ranged from 8.556% (row spacing 60 cm, plant spacing 11 cm, 15 plants/m²) to 9.074% (30 cm, 5 cm, 67 plants/m²), showing significant variation with row spacing and plant density (Table 4, Figure 1). The regression trend exhibited a U-shaped pattern, decreasing from 0 to

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~30 plants/m² then increasing to 80 plants/m² (R^2 = 0.4673), suggesting moderate density influence possibly due to competition-driven metabolic adjustments. Stearic Acid (Saturated): Stearic acid concentrations varied from 4.837% (row spacing 60 cm, plant spacing 5 cm, 33 plants/m²) to 5.649% (60 cm, 11 cm, 15 plants/m²), influenced significantly by row spacing and plant density (Table 4, Figure 1). The regression trend showed a decrease to ~40 plants/m² followed by a slight increase (R^2 = 0.4107), indicating density sensitivity with potential contributions from unmodeled factors.

Palmitoleic Acid (Monounsaturated): Palmitoleic acid, present in low amounts, ranged from 0.064% (row spacing 30 cm, plant spacing 8 or 14 cm, 42 or 24 plants/m²) to 0.173% (45 cm, 5 cm, 44 plants/m²), with significant effects from row spacing and plant density (Table 4, Figure 1). The regression trend peaked at 20–30 plants/m², declining on either side (R^2 = 0.3469), reflecting high variability and minimal density impact, likely dominated by environmental factors.

Oleic Acid (Monounsaturated): Oleic acid concentrations spanned 36.05% (row spacing 45 cm, plant spacing 11 cm, 20 plants/m²) to 40.85% (60 cm, 11 cm, 15 plants/m²), showing significant variation with row spacing and plant density (Table 4, Figure 1). The regression trend increased slightly to ~20 plants/m² then gradually declined (R^2 = 0.1513), suggesting complex interactions with factors like irrigation or soil nutrients.
Linoleic Acid (Polyunsaturated): Linoleic acid concentrations ranged from 43.49% (row spacing 60 cm, plant spacing 11 cm, 15 plants/m²) to 48.31% (30 cm, 8 cm, 42 plants/m²), significantly affected by row spacing and plant density (Table 4, Figure 1). The regression trend showed a consistent increase with density from 0 to 80 plants/m² (R^2 = 0.4633), likely due to enhanced photosynthetic efficiency or stress responses.
α-Linolenic Acid (Polyunsaturated): α-Linolenic acid, present in trace amounts, ranged from 0.193% (row spacing 45 cm, plant spacing 8 cm, 28 plants/m²) to 0.550% (45 cm, 11 cm, 20 plants/m²), with significant effects from row spacing and plant density (Table 4, Figure 1). The regression trend decreased sharply with increasing density (R^2 = 0.0394), indicating minimal density influence and high variability from other factors.
Arachidic Acid (Saturated): Arachidic acid concentrations varied from 0.324% (row spacing 45 cm, plant spacing 11 cm, 20 plants/m²) to 0.622% (45 cm, 5 cm, 44 plants/m²), showing significant variation with row spacing and plant density (Table 4, Figure 1). The regression trend decreased to ~40 plants/m² and then slightly increased (R^2 = 0.4437), suggesting moderate density influence with contributions from additional factors.
The significant RS × PS interaction ($P < 0.01$) affected all fatty acid profiles, emphasizing the importance of optimizing row spacing and plant spacing for specific fatty acid outcomes (Table 4). Low coefficients of variation (CV: 0.007%–4.590%) indicate high measurement precision. Moderate row spacings (45 cm) with plant spacings of 8–11 cm (20–28 plants/m²) optimized fatty acid profiles, particularly oleic and linoleic acids, critical for sesame oil's nutritional value. However, variable R^2 values from Figure 1 suggest additional environmental or genetic factors influence fatty acid composition, warranting further investigation.

Comparison of oil content (OC) correlations with fatty acids

The correlation matrix reveals distinct relationships between oil content (OC) and the fatty acid composition of sesame seeds, providing insights into how planting arrangements influence oil quality (Figure 2). OC exhibits a moderate positive correlation with linoleic acid (0.42**), indicating that higher oil yields are associated with increased levels of this essential omega-6 polyunsaturated fatty acid, which is nutritionally beneficial for cardiovascular health. This suggests that agronomic practices favoring higher oil production, such as denser planting arrangements (e.g., row spacing of 30 cm and plant spacing of 8 cm), may also enhance linoleic acid content, reflecting shared metabolic or environmental responses. In contrast, OC shows a strong negative correlation with oleic acid (-0.66**), highlighting a significant trade-off where higher oil content corresponds to lower oleic acid levels, crucial for oil stability and oxidative resistance. This inverse relationship, observed with oleic acid peaking at 40.85% under wider spacing (row spacing 60 cm, plant spacing 11 cm), suggests that maximizing oil yield might compromise oil shelf life. OC also shows a moderate positive correlation with palmitic acid (0.55**), indicating a slight increase in this saturated fat with higher oil content, though the effect is less pronounced than with linoleic acid. Weaker correlations include a negligible negative relationship with stearic acid (-0.10), a minor positive association with α-linolenic acid (0.19), and weak negative correlations with palmitoleic acid (0.13) and arachidic acid (-0.17), suggesting these fatty acids are less directly influenced by oil content variations or respond differently to planting density.

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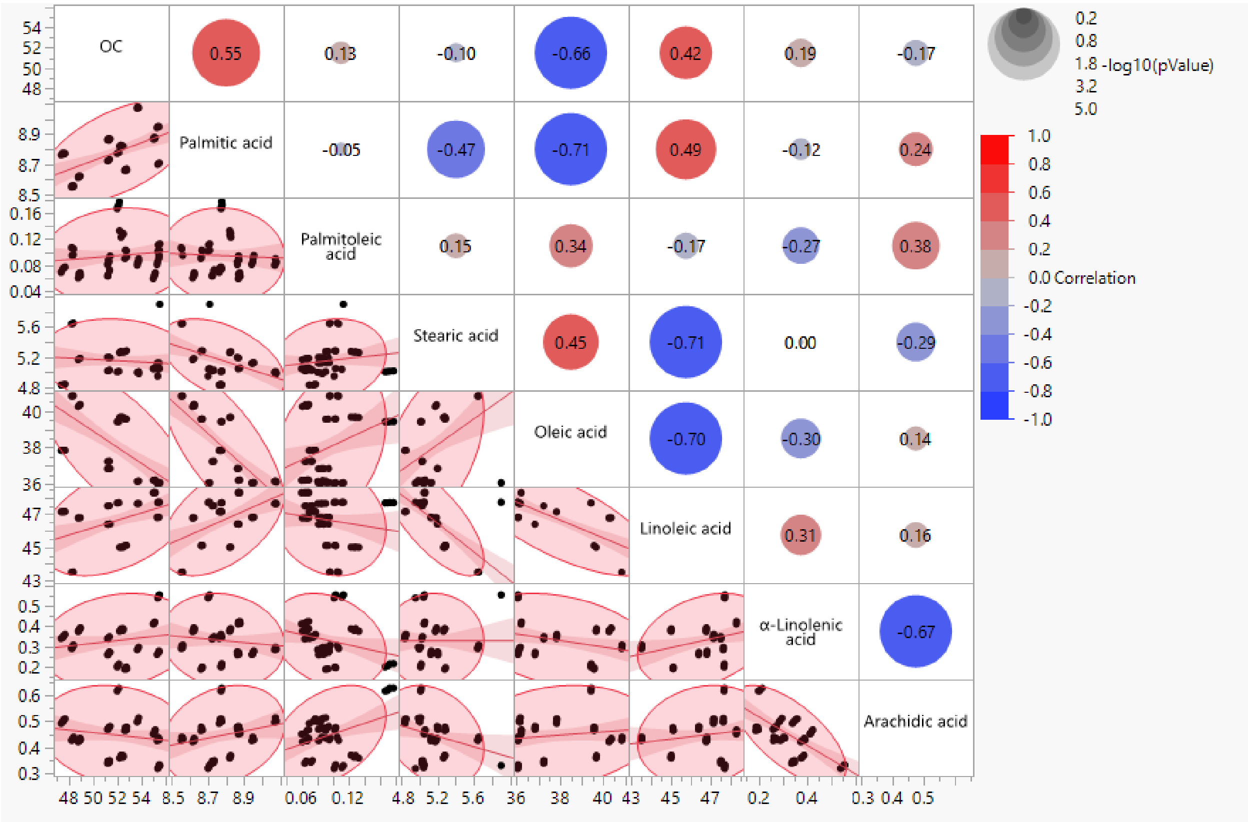

Figure 2. *Correlation heatmap of oil content and fatty acid composition in a non-shattering sesame cultivar*

Comparison of saturated, monounsaturated, and polyunsaturated fatty acids

The correlation matrix highlights complex interrelationships among saturated, monounsaturated, and polyunsaturated fatty acids, reflecting their competitive or complementary metabolic pathways in sesame oil under varying planting densities. Saturated fatty acids, such as palmitic (highest at 9.074% with row spacing 30 cm, plant spacing 5 cm), stearic (5.649% at row spacing 60 cm, plant spacing 11 cm), and arachidic (0.622% at row spacing 45 cm, plant spacing 5 cm), show mixed correlations with monounsaturated and polyunsaturated fats. Palmitic acid exhibits a strong negative correlation with oleic acid (-0.71**), a monounsaturated fat (peaking at 40.85% with row spacing 60 cm, plant spacing 11 cm), indicating a trade-off, while it shows a moderate positive correlation with linoleic acid (0.49**), a polyunsaturated fat (highest at 48.31% with row spacing 30 cm, plant spacing 8 cm), suggesting some alignment. Stearic acid, another saturated fat, has a moderate positive correlation with oleic acid (0.45**) but a strong negative correlation with linoleic acid (-0.71**), indicating competition with polyunsaturated fats but synergy with monounsaturated fats. Arachidic acid, a minor saturated fat, shows a moderate positive correlation with palmitoleic acid (0.38*), another monounsaturated fat (highest at 0.173% with row spacing 45 cm, plant spacing 5 cm), but a strong negative correlation with α-linolenic acid (-0.67**), a polyunsaturated fat (peaking at 0.55% with row spacing 45 cm, plant spacing 11 cm), highlighting distinct metabolic dynamics. Monounsaturated fats, like oleic and palmitoleic, show a moderate positive correlation (0.34*), suggesting alignment, but both have strong negative correlations with linoleic acid (-0.70** for oleic, -0.17 for palmitoleic), indicating a clear trade-off with polyunsaturated fats. Polyunsaturated fats, linoleic and α-linolenic, exhibit a moderate positive correlation (0.31*), reflecting their shared nutritional role, but both face competition from saturated and monounsaturated fats, particularly oleic acid, underscoring the need for strategic planting to balance these fatty acid profiles for nutritional and industrial purposes.

The results of the current work offer important new perspectives on how plant density and row spacing affect oil yield and fatty acid composition in a non-shattering sesame cultivar. The findings highlight areas for more research and line up with and expand current knowledge by providing useful advice for best sesame growing practices. The observed optimal combination of 45 cm row spacing and 8–11 cm plant spacing for maximizing oil content (55.45%) is consistent with prior research emphasizing the importance of moderate planting

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densities. For instance, Koocheki et al. (2017) demonstrated that a diamond planting pattern with 50 plants/m² enhanced dry matter and seed yield, while Öztürk and Şaman (2012) reported that narrower spacings (30 cm) combined with intra-row spacings of 5 cm maximized seed and oil yields in second-crop sesame. Similarly, Ali et al. (2020) found that narrower spacings improved performance under rainfed conditions, though wider spacings were better suited for irrigated systems. These findings corroborate the current study, which demonstrates that moderate row spacings (45 cm) combined with intermediate plant densities (8–11 cm) optimize oil content and maintain favorable fatty acid profiles. This underscores the need for region-specific planting strategies to balance resource use and productivity. The U-shaped response of palmitic acid to plant density, where concentrations initially decreased then increased at higher densities, presents a novel finding that complements earlier work by Bhardwaj et al. (2015) on shatter-resistant dwarf sesame. While their focus was primarily on oil yield characteristics, present research reveals how metabolic adjustments under varying competition levels specifically affect saturated fatty acid biosynthesis. This observation gains additional significance when compared with findings from Alpaslan et al. (2001), who demonstrated row spacing effects on sesame seed composition but did not explore the complex density-dependent relationships documented here. Current results regarding linoleic acid's consistent increase with density (43.49%–48.31%) corroborate and expand upon Ali et al. (2020) work in semi-arid regions, where narrower row spacings enhanced sesame performance under rainfed conditions. The moderate positive correlation between oil content and linoleic acid ($r = 0.42^{**}$) suggests a physiological mechanism where increased photosynthetic efficiency at higher densities directly influences polyunsaturated fatty acid biosynthesis. This relationship is particularly relevant given linoleic acid's crucial role in cardiovascular health, as emphasized by Gouveia et al. (2017). The strong negative correlation between oleic and linoleic acids ($r = -0.70^{**}$) documented in this study provides empirical support for the competitive nature of fatty acid biosynthesis pathways previously suggested by Kim et al. (2006) and Tas et al. (2024). Their work on drought stress and nitrogen application effects showed similar inverse relationships, though current findings specifically attribute these dynamics to planting arrangement variations. This insight has practical implications for breeding programs aiming to develop sesame varieties with specific fatty acid profiles, as noted by Rauf et al. (2024) in their comprehensive review of sesame breeding achievements. The observed decrease in α-linolenic acid with increasing density, despite showing poor model fit ($R^2 = 0.0394$), contrasts with findings from Tas et al. (2024), who demonstrated significant effects of drip irrigation and nitrogen levels on sesame oil composition. This discrepancy suggests that while agronomic practices like irrigation and fertilization significantly influence α-linolenic acid levels, planting arrangements may have minimal direct impact. The low variability explained by the present model indicates other environmental or genetic factors might play more substantial roles in determining this nutritionally important omega-3 fatty acid's concentration. Results of arachidic acid's response to planting density, showing a decreasing trend followed by a slight increase, provide new data that complements earlier work by El Harfi et al. (2021) on genetic diversity in Moroccan sesame. The moderate R^2 value (0.4437) suggests that while density influences arachidic acid levels, other genetic or environmental factors also contribute significantly. This finding aligns with observations from Filimon and Worku (2018) regarding optimum inter-row spacing for sesame production under irrigation, though our study offers more precise data on how specific planting arrangements affect individual fatty acids. The complex interrelationships among different fatty acids revealed through current correlation analysis, particularly the strong negative correlations between stearic and linoleic acids ($r = -0.71^{**}$) and between oleic and linoleic acids ($r = -0.70^{**}$), highlight fundamental trade-offs in fatty acid biosynthesis. These findings complement earlier work by Koocheki et al. (2017) on planting patterns and density effects but provide more detailed biochemical insights. The observed relationships have significant ramifications for sesame breeding programs and agricultural policy development, especially considering Iran's emerging influence in the global sesame market, as discussed by Gholamhoseini and Dolatabadian (2024). The practical applications of present findings are particularly relevant for regions facing similar semi-humid, moderately warm climatic conditions as this study site. Present recommendations for 45 cm row spacing and 8–11 cm plant density offer clear guidelines for maximizing oil yield and quality, extending beyond general suggestions from Ngala et al., (2013) about inter-row spacing and plant density effects in Nigerian Sudan Savanna conditions. Furthermore, the documented relationships between planting arrangements and fatty acid profiles can inform processing industries about expected oil characteristics based on cultivation practices, supporting sustainable sesame production systems as emphasized by Sanni et al. (2024). The study's limitations, particularly regarding environmental factors not fully controlled during the experimental period, suggest avenues for future research. While meteorological data was recorded and soil properties analyzed, variations in microclimate conditions and subtle differences in field management could have influenced results. Future research should incorporate multi-year and multi-location trials to account for these variables, building

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on methodological approaches suggested by Abeje et al. (2020) in their soybean spacing studies. Additionally, molecular approaches could help elucidate the genetic mechanisms underlying observed responses to planting arrangements, complementing recent advances in sesame genomics documented by Yol et al. (2021) and Teboul et al. (2022). The implications of these findings extend to economic analyses of recommended practices under different market conditions. As noted by Mohammadi et al. (2013) regarding Iran's edible oil imports, optimizing local sesame cultivation could significantly impact national food security and economic sustainability. Results of the current study provide concrete data to support strategic decisions in expanding sesame cultivation, particularly in arid and semi-arid regions where water-efficient crops are crucial, as emphasized by Gholamhoseini (2022) in his work on irrigation and nitrogen optimization. Future research directions should focus on integrating obtained findings with broader agronomic strategies. Long-term studies incorporating multiple environmental variables, as suggested by Khan and Islam (2023) in their row spacing performance analysis, would provide more comprehensive optimization strategies. Additionally, exploring the interactions between planting arrangements and other agronomic factors such as irrigation scheduling and nutrient management could build upon current findings and contribute to developing sustainable sesame production systems, as emphasized by Wacal et al. (2024) in their comprehensive review of sesame's potential benefits

CONCLUSION

This study demonstrates that optimizing planting arrangements, specifically moderate row spacings combined with plant spacings, significantly enhances oil content and maintains desirable fatty acid profiles, particularly oleic and linoleic acids, in the non-shattering sesame cultivar 'Mohajer' under semi-humid conditions in Moghan, Iran. The significant interaction between row spacing and plant density underscores their combined impact on oil yield and composition, with regression analyses revealing density-dependent trends, though variable values suggest additional environmental or genetic influences. These findings offer practical recommendations for Iranian farmers to improve local sesame production, reducing reliance on imported edible oils, while highlighting the need for further multi-year and molecular studies to refine cultivation strategies and address variability in fatty acid biosynthesis, ultimately supporting sustainable agriculture and food security in arid and semi-arid regions.

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CONFLICT OF INTEREST

The Authors declares that there are no conflicts of interest.

AUTHOR CONTRIBUTION

Conceptualization: HZT; Data collection: HZT, FS; Analysis and interpretation of results: HZT, FS; Writing - original draft: HZT, FS;Writing - review & editing: HZT, FS, AP. All authors reviewed and approved the final version of the manuscript.

ETHICAL APPROVAL

This research study complies with research and publishing ethics. The scientific and legal responsibility for manuscripts published in MJAVL belongs to the author(s).

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