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The Effect of Drip Irrigation and Nitrogen Levels on the Oil and Fatty Acid Composition of Sesame and Its Economic Analysis

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Abstract: One of the oldest oilseed crops is sesame, which is mainly cultivated due to its valuable oleic/linolenic fatty acid ratio. The application of precise irrigation and fertilisation is crucial to ensure the continuity and productivity of sesame production, especially in arid and semi-arid regions. This study aimed to determine the effect of drip irrigation and nitrogen levels on sesame's oil and fatty acid composition. For this purpose, four nitrogen doses (N_0: 0 kg ha^{-1}, N_{30}: 30 kg ha^{-1}, N_{60}: 60 kg ha^{-1} and N_{90}: 90 kg ha^{-1}) and three different irrigation water levels (I_{50}, I_{75} and I_{100}, which correspond to 50, 75 and 100% evaporation levels from the evaporation of the Class A pan) were applied. The highest oleic acid content (43.06%) was obtained for the $I_{75}N_{90}$ treatment. In the case of linoleic fatty acid, the greatest value (43.66%) was for $I_{50}N_0$ treatment. The effects of irrigation and nitrogen doses on oleic acid and linoleic acid content were inverse of each other. An increase in applied irrigation water increased the linoleic acid content. However, it caused a decrease in oleic acid content. Increasing the nitrogen dose increased the oleic acid content and caused a decrease in linoleic acid content. Furthermore, this study showed that the $I_{50}N_{60}$ treatment (50% Epan and a rate of 60 kg N ha^{-1}) is the most effective for achieving high grain and oil yields in sesame cultivation. The results obtained provide practical guidance for farmers in sesame cultivation.

Keywords: fatty acid; irrigation; nitrogen; water use efficiency; economic water productivity; benefit/cost ratio

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1. Introduction

Agricultural production currently faces many problems due to increasing population, urbanisation and climate variability. Water, the most essential for all sectors, is under tremendous pressure in quantity and quality, and this problem is predicted to grow much more significantly in the future [1]. Supplying water of suitable quality and sufficient quantity for production becomes more difficult each year. In places with insufficient rainfall, the missing water must be applied to the soil through irrigation to ensure good plant growth or increase productivity. Many different factors must be considered together when irrigating plants. Irrigation time and the amount of irrigation water should be precisely determined based on research and determination of the plant's water needs [2–4]. Irrigating plants using the right methods and correct timing has a positive impact on yields, as well as their quality. It also reduces production costs and increases profitability [5].

On the other hand, improper irrigation causes water and soil resources to be wasted, environmental problems (such as salinisation, erosion, groundwater pollution and ecology degradation) and a negative impact on their sustainable use. Nowadays, as our world is rapidly heading towards water scarcity, studies focusing on obtaining maximum benefit from every drop of water are crucial [6,7]. This is vital not only in terms of water but also of food production to meet human demand.

Another important input of agricultural production is fertilisers. Nitrogenous fertilisers are the most crucial fertiliser in crop production [8]. The prices of all fertilisers used in agricultural production worldwide are increasing. This significantly increases the cost of production. As a result, producers are using less fertiliser, so the plants are not growing enough. Sometimes, excessive fertilisation, especially of nitrogenous fertilisers, increases production costs and causes pollution of natural resources (especially shallow groundwater and deep groundwater). When application times and doses of nitrogenous fertilisers are not followed, severe losses in production are caused. Increased moisture availability and N application are reported to improve nitrate reductase activity, nitrogen uptake and nitrogen use efficiency. It has been shown that supplementary irrigation with minimal water in the early growth phase leads to a significant increase in seed yields due to efficient use of nutrients in the event of drought [9]. Adequate nitrogen fertiliser application also increases the uptake of other nutrients (especially phosphorus and potassium) and some micronutrients [10]. In sesame cultivation, too little or too much of the applied irrigation water and nitrogenous fertiliser can cause significant losses in yield. In addition, water stress in sesame increases under conditions where nitrogen fertiliser use is high [11]. Since irrigation and nitrogen fertiliser use are essential factors in field agriculture, they must be optimised.

Sesame (*Sesamum indicum* L.) is suitable for irrigated and rainfall cultivation. However, it has been found to give significantly better yields under irrigated conditions than without [12]. On the other hand, excessive irrigation negatively affects sesame yield [13]. Moreover, drought stress is one of the most critical environmental factors limiting sesame production [14]. Sesame grains, which have low irrigation water needs and are resistant to heat stress, are a valuable nutrient, and their oil is among the most beneficial. Sesame is one of the oldest and most important oil plants cultivated in the world, with a high quantity and quality of oil in its seeds [15]. One of the essential properties of sesame oil is its resistance to oxidative degradation [16].

According to 2021 FAOSTAT data, sesame seed production accounts for a worldwide total area of 8,980,339 ha producing 6,354,477 tons. Moreover, approximately 7 million tons of oil are produced. This oil is rich in various nutrients and minerals, such as copper, manganese, calcium, and iron, and it is widely used in bread, pasta, and dessert. Furthermore, sesame can be considered an alternative plant to eliminate people's nutritional deficiencies in water shortage conditions. However, to ensure the sustainable continuity of production, especially in arid and semi-arid regions, establishing an irrigation program with drip irrigation that provides the most water savings and determining the most appropriate nitrogen dose is vital for the future.

This study aimed to determine the effects of drip irrigation and nitrogen levels on sesame oil and fatty acid composition. In this research, different nitrogen doses for the sesame plant (0, 30, 60 and 90 $\text{kg}\cdot\text{ha}^{-1}$ pure nitrogen) and different restricted irrigation (I_{50}, I_{75} and I_{100}) applications were made. Changes in sesame yield and seed oil content were examined. Furthermore, an economic analysis was carried out on the above treatments.

2. Materials and Methods

2.1. Study Area

The study was conducted in Turkey at Çanakkale Onsekiz Mart University, Faculty of Agriculture, Plant Production Research and Application Unit. The characteristics of the soil of the experimental area are given in Table 1. The cultivated soils had a structure of mainly clay loam, were calcareous, had a neutral reaction and had low organic matter content. The trial area's soil was evaluated regarding plant nutrients, and appropriate fertilisation was applied. The research was conducted in 2020–2021.

Table 1. Soil characteristics of the experimental site.

Depth (cm)	0–30	30–60	60–90
Texture	Clay-Loam	Clay-Loam	Sand-Clay-Loam
Saturation (%)	48.93	59.40	40.30
pH	7.78	8.08	8.11
EC ($dS\cdot m^{-1}$)	0.48	0.44	0.85
Lime (%)	12.01	18.10	14.80
Organic matter (%)	1.49	1.74	1.91
Phosphorus (kg $P_2O_5\cdot ha^{-1}$)	470.58	390.63	380.62
Potassium (kg $K_2O\cdot ha^{-1}$)	620.17	860.48	300.23
FC (%)	32.80	36.20	35.10
PWP (%)	19.80	22.60	22.50
BD ($g\cdot cm^{-3}$)	1.43	1.39	1.46

EC: Electrical Conductivity; FC: Field Capacity; PWP: Permanent Wilting Point; BD: Bulk Density; AW: Available Water.

2.2. Climate

The region where the research was conducted generally has a temperate climate. Due to its location, it has a transitional climate between the Mediterranean and Black Sea climates. Information on climate parameters was obtained from the Çanakkale Meteorology Directorate. The monthly average values of climate parameters for 1937–2019 are presented in Table 2. As can be seen from the table, the average relative humidity value of Çanakkale for the years 1937–2019 was 73.3%. The average temperature was 15.0 °C, and the average rainfall was 628.8 mm. The lowest measurable daily temperature was recorded as −11.5 °C on 2 February 1929, and the highest was 39.7 °C on 1 August 2021. The maximum sunshine duration was 12.6 h in July, and the lowest was 3.1 h in January. The average annual open-water surface evaporation amounted to 1290.1 mm.

Table 2. Long-term (1937–2019) averages for climate parameters of Canakkale province.

Months	Temperature (°C)			Relative Humidity RH (%)	Wind Speed R ($m\cdot s^{-1}$)	Rainfall (mm)	Evaporation (mm)
	Mean	Max	Min				
January	6.3	9.7	3.2	80.0	4.5	93.7	- *
February	6.7	10.3	3.5	78.5	4.7	71.7	- *
March	8.3	12.4	4.8	77.0	4.3	68.3	- *
April	12.6	17.2	8.5	75.0	3.8	47.0	110.0
May	17.6	22.6	12.8	73.2	3.4	32.0	168.3
June	22.3	27.8	16.7	67.6	3.3	22.4	217.0
July	25.1	30.7	19.4	62.9	3.8	11.7	268.3
August	25.0	30.6	19.6	63.3	4.0	6.5	252.2
September	20.9	26.4	15.9	68.0	3.7	24.2	170.8
October	16.0	20.7	12.1	74.3	3.7	57.0	103.5
November	11.9	15.9	8.4	78.7	3.9	86.1	- *
December	8.5	11.8	5.4	80.3	4.4	108.2	- *
Aver/Total	15.1	19.7	10.9	73.2	4.0	628.8	1290.1

* Open-water evaporation is not measured in winter months.

The results of the climate parameters measured during the research years are shown in Table 3. In the second year of the research, the highest daily average temperature record was broken. The average difference of the trial years was 1 °C in temperature, 2% in relative humidity and 1 m·s^{-1} in wind speed. However, the amount of precipitation in the experimental years was very different: 457 mm in the first year and 753 mm in the second year.

Table 3. Average climate parameters in Canakkale province for years 2020 and 2021.

Months	Temperature (°C)			Relative Humidity RH (%)	Wind Speed R (m·s^{-1})	Rainfall (mm)	Evaporation (mm)
	Mean	Max	Min				
2020							
January	7.3	11.5	4.3	67.6	3.7	57.2	39.5
February	9.7	14.0	6.0	69.3	4.1	48.0	37.3
March	11.7	16.1	8.1	68.6	3.6	24.3	61.6
April	12.3	17.7	8.0	68.2	3.7	55.7	119.5
May	18.2	23.6	13.5	68.9	3.0	54.6	151.9
June	22.6	28.4	17.8	74.0	3.0	38.8	213.7
July	27.0	32.9	21.7	55.3	4.1	0.1	341.2
August	27.1	33.4	21.6	54.2	3.5	3.2	300.1
September	24.7	29.7	20.6	59.6	3.5	9.5	229.9
October	19.3	24.7	14.8	77.5	4.0	51.3	129.6
November	12.7	17.0	9.2	79.4	2.5	0.7	96.9
December	11.5	14.4	9.2	87.3	3.4	113.8	47.4
Avg/Total	17	22	13	69	4	457	1769
2021							
January	9.8	13.2	6.8	74.8	5.0	165.3	91.2
February	9.1	13.4	5.8	75.8	4.7	124.7	68.5
March	9.2	14.0	5.1	79.1	3.0	74.0	50.6
April	13.1	18.2	9.0	88.6	3.1	40.4	95.4
May	19.9	25.2	16.0	66.6	3.1	57.3	181.7
June	24.1	29.3	19.5	58.3	2.0	57.1	193.0
July	28.2	33.8	23.5	52.0	2.7	2.0	314.5
August	28.3	33.4	24.1	51.1	2.3	0.0	289.8
September	23.1	27.6	19.1	54.0	2.7	8.9	233.7
October	18.1	21.5	15.4	64.8	2.7	75.9	119.6
November	15.8	19.1	13.0	68.2	3.3	26.7	77.3
December	12.2	14.8	9.8	68.7	4.2	121.0	55.7
Avg/Total	18	22	14	67	3	753	1771

2.3. Field Experiment

The muganlı-57 sesame variety, which is compatible with the region, was used as the plant material for this study. The research was set up in a split-plot experimental design in randomised blocks with four replications. The measurements were carried out on sesame plants to investigate the effects of four nitrogen doses (N_0: 0, N_{30}: 30, N_{60}: 60 and N_{90}: 90 kg ha^{-1}) and three different irrigation water levels (50, 75 and 100% of evaporation level from the evaporation of class A pan). Field trials were conducted in two growing seasons in 2020 and 2021. Plants were planted with 40 cm spacing between plants and 20 cm between rows. In the trials, planting was done on 12 m^2 (2.4 m × 5 m) parcels consisting of 6 rows, with a calculation of 15 kg ha^{-1}. Sesame seeds were planted at a planting depth of 1 cm after careful soil preparation. A distance of 2 m was left between the plots to prevent transfer between irrigation and fertiliser doses. In the experiments, irrigation levels were used in the main plots, and nitrogen doses were used in the sub-plots. In both growing seasons, 8 kg da^{-1} pure phosphorus was applied with triple super phosphate fertiliser before planting, and ammonium nitrate fertiliser was used as the nitrogenous fertiliser. Application of the first dose, which was 1/3 of the total dose of nitrogen, was given at planting; 1/3 after emergence, when the plants reached a height of approximately 20 cm; and the remaining 1/3 was given before cluster emergence. After planting in both growing seasons, water was applied equally to all plots with a drip irrigation system to ensure the emergence of plants in the trial plots. Weed control was carried out by hoeing and hand plucking throughout the season. When the plants reached harvest maturity, the harvest was done manually, and the threshing process was done using a threshing machine (Mono Makine, Ankara, Turkey). Moreover, in field trials, plant height, biological yield, thousand-grain weight, harvest index, number of grains per cluster, grain weight per cluster and grain yield were examined.

2.4. Irrigation System and Treatments

A drip irrigation system was designed for the experiment. Laterals were laid for each plant row, and inline emitters (pressure compensating) with a discharge rate of 1.6 L/h were spaced at 40 cm intervals on the lateral line. The system was operated at 2 bar (200 kPa) throughout the growing season. The system's control unit consisted of a pump, hydrocyclone, fertiliser tank, disk filters, control valves, pressure gauges and a flow meter (Sunstream by Isko Plastic, Canakkale, Turkey).

In the first irrigation, soil moisture was brought to field capacity. Afterwards, all treatments were given approximately equal amounts of irrigation water until the plant roots developed. After the plants achieved sufficient growth, regular irrigation was started. The amount of water given during the irrigation treatments was determined using a Class A evaporation pan placed in the test area: 50% (I_{50}), 75% (I_{75}) and 100% (I_{100}) levels of the weekly values of the measured cumulative open-water surface evaporation values converted to the reference evapotranspiration (ET_0) value were applied. The following equation suggested by Brouwer and Heibloem [17] was used to calculate the amount of irrigation water.

$$I = E\ pan \times K\ pan \tag{1}$$

where I: amount of irrigation water to be applied (mm); E pan: pan evaporation (mm); and K pan: pan coefficient (or the Class A evaporation pan, the K pan varies between 0.35 and 0.85; average K pan = 0.70).

In the control of the given irrigation water, the following equation was used, considering the pressure-dripper flow rate–time relationship, in line with the recommendations of Eylen et al. [18].

$$T = \frac{I \times A}{q \times n} \tag{2}$$

where T: irrigation water application time (hours); I: amount of irrigation water to be applied (mm); A: parcel area (m^2); q: dripper flow rate at operating pressure (litre·hour^{-1}); and n: number of drippers in the parcel (piece).

2.5. Calculation of Evapotranspiration

The water budget equation given by James [19] was used to determine plant water consumption in the trial treatments:

$$ET = I + R + Cr - Dp - Rf \pm \Delta s \tag{3}$$

where ET: plant water consumption (mm); I: irrigation water (mm); R: effective precipitation (mm); Cr: capillary rise (mm); Dp: deep infiltration losses (mm); Rf: surface flow losses (mm); and Δs: moisture change in the soil profile (mm).

Deep infiltration and capillary rise were monitored by gravimetric soil moisture sampling up to 120 cm deep at 2-week intervals. No change in soil moisture at this depth was detected.

2.6. Determination of Water and Irrigation Water Use Efficiency

By recording the irrigation water and efficiency values applied throughout the season, water use efficiency (WUE) and irrigation water use efficiency (IWUE) for each irrigation subject were calculated with the equations given below [20–22]. These parameters are important and commonly used in irrigation efficiency studies [23–26].

$$\mathrm{IWUE} = \mathrm{Y}/\mathrm{I} \tag{4}$$

$$\mathrm{WUE} = \mathrm{Y}/\mathrm{ETa} \tag{5}$$

where IWUE: irrigation water use efficiency ($\mathrm{kg{\cdot}ha\ mm^{-1}}$); Y: yield ($\mathrm{kg{\cdot}ha^{-1}}$), I: amount of irrigation water applied (mm); WUE: water use efficiency ($\mathrm{kg{\cdot}ha\ mm^{-1}}$); and ETa: actual plant water consumption (mm).

2.7. Crop Water Productivity

Crop water productivity (CWP) is defined using various terms from different researchers [27–29]. CWP is the product's amount or value over the water consumed or diverted. In this work, CWP was calculated as the ratio of actual plant yield to the volume of water used:

$$\mathrm{CWP} = \mathrm{Y}/\mathrm{ETa} \tag{6}$$

where CWP: crop water productivity expressed as $\mathrm{kg{\cdot}m^{-3}}$ per unit water volume; Y: yield ($\mathrm{kg{\cdot}ha^{-1}}$); and ETa: actual evapotranspiration ($\mathrm{m^3{\cdot}ha^{-1}}$).

2.8. Economic Water Productivity (EWP)

For the economic water productivity, the following equation given by Tewelde [30] was used in the calculation:

$$\mathrm{EWP} = \mathrm{GI}/\mathrm{IW} \tag{7}$$

$$\mathrm{GI} = (\mathrm{PTG} * \mathrm{YLDg}) \tag{8}$$

where EWP: economic water productivity ($\mathrm{\${\cdot}m^{-3}}$); GI: total income ($\mathrm{\${\cdot}ha^{-1}}$); IW: irrigation water ($\mathrm{m^3\ ha^{-1}}$); PTG: sesame sales price ($\mathrm{\${\cdot}ton^{-1}}$); and YLDg: yield received ($\mathrm{ton{\cdot}ha^{-1}}$).

The values used in the cost and income calculations include local production costs and sales prices of the years in which the research was conducted.

2.9. Crude Oil and Fatty Acid Composition

The harvested samples were immediately dried and ground (IKA MF 10.1, Staufen, Germany) and prepared for analysis. Samples were stored at +4 °C during analysis [31].

The oil was reported as % of seed weight standardised to 10.0% moisture. Samples of 5.0 ± 0.05 g were selected for each application. The sample was then placed in a double paper filter cartridge and subjected to organic solvent-based extraction using petroleum ether (80 mL) as the extraction solvent. The extraction process was carried out for 8 h using butt-type extraction equipment. The cartridge was disposed of, and the miscella (a mixture of oil and solvent) was separated using rotary evaporation at 40–50 °C. The residual solvent was removed using a stream of nitrogen, and the balloon holding the lipids was then placed in a drying oven at a temperature of 100 ± 5 °C for 1 h. After cooling, the balloon was weighed. The oil content of the seeds was assessed by gravimetric measurement of the recovered oil and expressed as a weight percentage relative to the original weight of the oilseeds. The analyses were conducted twice.

Proportional FA compositions of oil were determined in their FA methyl esters (FAME), according to Ackman [32] and Bannon et al. [33]. Oil samples (0.3 to 0.5 mL) were mixed with 1.5 mL of 0.5 N methanolic NaOH for 7 min at 115 °C. After cooling, 2 mL of boron trifluoride was added and heated for another 5 min at the same temperature. Test tubes were cooled, and 2 mL of iso-octane and 3 mL of saturated NaCl solution were added and mixed for 30 s. The samples were then allowed to separate from the organic phase.

The FAME's were extracted from the top layer and transferred into the amber vial for further gas chromatography (GC) analysis. FAME extracts were kept in a freezer at −20 °C until GC analysis. The FAME was analysed by a GC (Agilent 7697A, Agilent Technologies, Santa Clara, CA, USA) fitted with a flame ionisation detector. The FAME separated with a capillary HP-FFAP column (J&W 19091F–433, Agilent Technologies, USA; 30 m × 0.25 mm i.d; 0.25 µm film thickness). Hydrogen was the carrier gas at a flow of 3 mL·min^{-1}. The initial set oven temperature was 100 °C. It was programmed to increase up to 240 °C at a rate 10 °C·min^{-1}. The sample volume was 2 µL, and the inlet temperature was 225 °C. The split ratio was 100:1. The identification of individual FAME was done by retention time compared to standard FAME mix (Supelco 37 component FAME mix, Sigma-Aldrich Chemie GmbH, Taufkirchen, Germany) and was reported as proportional to the total FAME. Each sample was injected twice by the GC autosampler [8].

2.10. Statistical Analysis

The plant characteristics measured in the research were subjected to analysis of variance separately for each year. The data collected in this study were subjected to analysis of variance (ANOVA) using PROC GLM of the SAS version 9.0 (SAS Institute, Cary, NC, USA), and the least significant difference (LSD) was used to compare means of traits ($p < 0.05$). Then, regression analysis was performed separately to visually evaluate the nitrogen × irrigation dose interactions of vegetative traits, oil content and fatty acid composition.

3. Results

3.1. Water Use Efficiency and Economic Analysis

The efficiency and economic indicators of irrigation water used in crop production are vital for the sustainability of production. The irrigation water applied to the treatments in the study, the measured actual evapotranspiration, the calculated water use efficiency and the results of the economic indicators are shown in Table 4. We applied 263, 394 and 525 mm of irrigation water to the treatments (I_{50}, I_{75} and I_{100}, respectively) in 2020 and 248, 372 and 496 mm in 2021. On the other hand, ETa values varied between 343–590 mm in 2020 and 323–566 mm in 2021. It was determined that the ETa value of the plants increased depending on the increasing amount of irrigation water and nitrogen dose. The highest ETa values were obtained from the treatments where the most irrigation water and nitrogen were applied (I_{100} N_{90}). IWUE values changed by 0.22–1.24 kg ha^{-1} m^{-3}. The lowest IWUE values were calculated for the I_{100} N_0 treatments in both years of the experiment. In the first year of the experiment, 0.26–0.66 kg ha^{-1} m^{-3} was obtained, and in the second year, 0.22–1.24 kg ha^{-1} m^{-3} was obtained. According to the calculations, the lowest IWUE values were achieved for $I_{100}N_{90}$. The highest values were obtained for $I_{75}N_{60}$. A similar situation was also for the WUE value. WUE values varied between 0.20–0.87 kg ha^{-1} m^{-3}; the lowest WUE values were obtained for $I_{100}N_{90}$ and the highest for the $I_{75}N_{60}$ treatment. Economic indicators were calculated using the method detailed in Tas (2023) [34]. As a result, EWP values varied between 0.51 and 2.80 in the first year and 0.41 and 2.38 $ m^{-3} in the second year. In both years, I_{100} treatments had the lowest EWP values. The highest EWP values were obtained for the $I_{50}N_{60}$ treatment. A similar situation occurred for the B/C ratio in EWP. The B/C ratio varied between 1.10 and 3.84 in the first year and 0.94 and 3.49 in the second year. In both years, the I_{100} treatment gave the lowest B/C values. The highest B/C values were obtained for $I_{50}N_{60}$.

Irrigation and fertiliser applications are the two most essential parameters in plant development. These applications can cause significant changes in the plant's morphology, yield and quality. Different irrigation water levels and nitrogen dose applications have caused significant changes in the sesame plant. In this study, the change in sesame grain yield generally differed depending on nitrogen doses at each irrigation level (Table 5 and Figure 1). In both trial years, the lowest grain yields were obtained from I_{100} irrigation water application and 0 kg ha^{-1} nitrogen application. The highest yields were for I_{50} irrigation water level and 60 kg ha^{-1} nitrogen treatments. The yields reached 3.2 tons ha^{-1}

in 2020 and 3.1 tons ha^{-1} in 2021. While grain yield was lowest at the lowest nitrogen dose, it increased depending on nitrogen applications. However, it decreased at the highest level of nitrogen dose (90 kg ha^{-1}). The change in grain yield of sesame for I_{75} and I_{100} irrigation applications was generally similar, although the lowest and highest values were different. The highest grain yield was achieved at 30 kg ha^{-1} nitrogen application at both irrigation levels in both trial years. However, grain yields obtained for the I_{75} application were higher than the $I1_{00}$ application.

Table 4. Yield and morphological characteristics.

Year	Nitrogen Dose (kg ha^{-1})	Irrigation Water Level	Irrigation Water (mm)	ETa (mm)	IWUE (kg ha^{-1} m^{-3})	WUE (kg ha^{-1} m^{-3})	Economic Water Productivity ($ m^{-3})	The Benefit-to-Cost (B/C) Ratio
2020	0	I_{50}	263	343	0.57	0.44	1.3	1.79
2020	0	I_{75}	394	454	0.66	0.57	1.50	2.72
2020	0	I_{100}	525	563	0.26	0.24	0.59	1.28
2020	30	I_{50}	263	362	0.84	0.61	1.92	2.63
2020	30	I_{75}	394	470	0.72	0.61	1.65	2.99
2020	30	I_{100}	525	574	0.38	0.34	0.86	1.85
2020	60	I_{50}	263	379	1.23	0.85	2.80	3.84
2020	60	I_{75}	394	484	0.64	0.52	1.45	2.63
2020	60	I_{100}	525	581	0.33	0.30	0.75	1.63
2020	90	I_{50}	263	395	0.93	0.62	2.11	2.89
2020	90	I_{75}	394	497	0.53	0.42	1.21	2.20
2020	90	I_{100}	525	590	0.22	0.20	0.51	1.10
2021	0	I_{50}	248	323	0.6	0.46	1.14	1.68
2021	0	I_{75}	372	430	0.52	0.45	1.00	1.93
2021	0	I_{100}	496	532	0.22	0.20	0.41	0.94
2021	30	I_{50}	248	341	1.04	0.76	1.99	2.92
2021	30	I_{75}	372	444	0.74	0.62	1.42	2.74
2021	30	I_{100}	496	546	0.38	0.35	0.73	1.66
2021	60	I_{50}	248	355	1.24	0.87	2.38	3.49
2021	60	I_{75}	372	457	0.58	0.47	1.11	2.15
2021	60	I_{100}	496	560	0.28	0.25	0.53	1.21
2021	90	I_{50}	248	371	0.81	0.54	1.55	2.28
2021	90	I_{75}	372	470	0.49	0.39	0.94	1.81
2021	90	I_{100}	496	566	0.27	0.23	0.51	1.17

Table 5. Effects of different nitrogen and water applications on vegetative characteristics of sesame.

Nitrogen Dose (kg ha^{-1})	Irrigation Water Level	Grain Yield (t ha^{-1})	Plant Height (cm)	Number of Main Branches Plant^{-1}
		2020		
0	I_{50}	1.5	129.3	6.8
0	I_{75}	2.6	139.0	6.6
0	I_{100}	1.4	133.0	3.8
30	I_{50}	2.2	143.0	9.3
30	I_{75}	2.9	139.0	6.9
30	I_{100}	2.0	147.0	6.6
60	I_{50}	3.2	158.0	8.4
60	I_{75}	2.5	143.3	9.0
60	I_{100}	1.7	165.7	4.0
90	I_{50}	2.4	165.3	8.2
90	I_{75}	2.1	152.3	7.6
90	I_{100}	1.6	170.7	4.2

Table 5. *Cont.*

Nitrogen Dose (kg ha^{-1})	Irrigation Water Level	Grain Yield (t ha^{-1})	Plant Height (cm)	Number of Main Branches Plant^{-1}
		2021		
0	I_{50}	1.5	109.3	3.7
0	I_{75}	2.0	118.3	3.0
0	I_{100}	1.1	123.0	2.7
30	I_{50}	2.6	126.3	5.7
30	I_{75}	2.8	120.3	3.3
30	I_{100}	1.9	129.7	5.7
60	I_{50}	3.1	122.0	3.7
60	I_{75}	2.2	127.7	5.7
60	I_{100}	1.4	159.7	3.0
90	I_{50}	2.0	132.3	2.7
90	I_{75}	1.8	159.0	3.7
90	I_{100}	1.3	160.0	3.3
	0	1.7	125.3	4.4
	30	2.4	134.2	6.3
	60	2.4	146.1	5.6
	90	1.8	156.6	4.9
	LSD (0.01)	0.20	11.13	0.80
	I_{100}	1.5	148.6	4.2
	I_{50}	2.3	135.7	6.0
	I_{75}	2.3	137.4	5.7
	LSD (0.01)	0.10	8.05	1.19

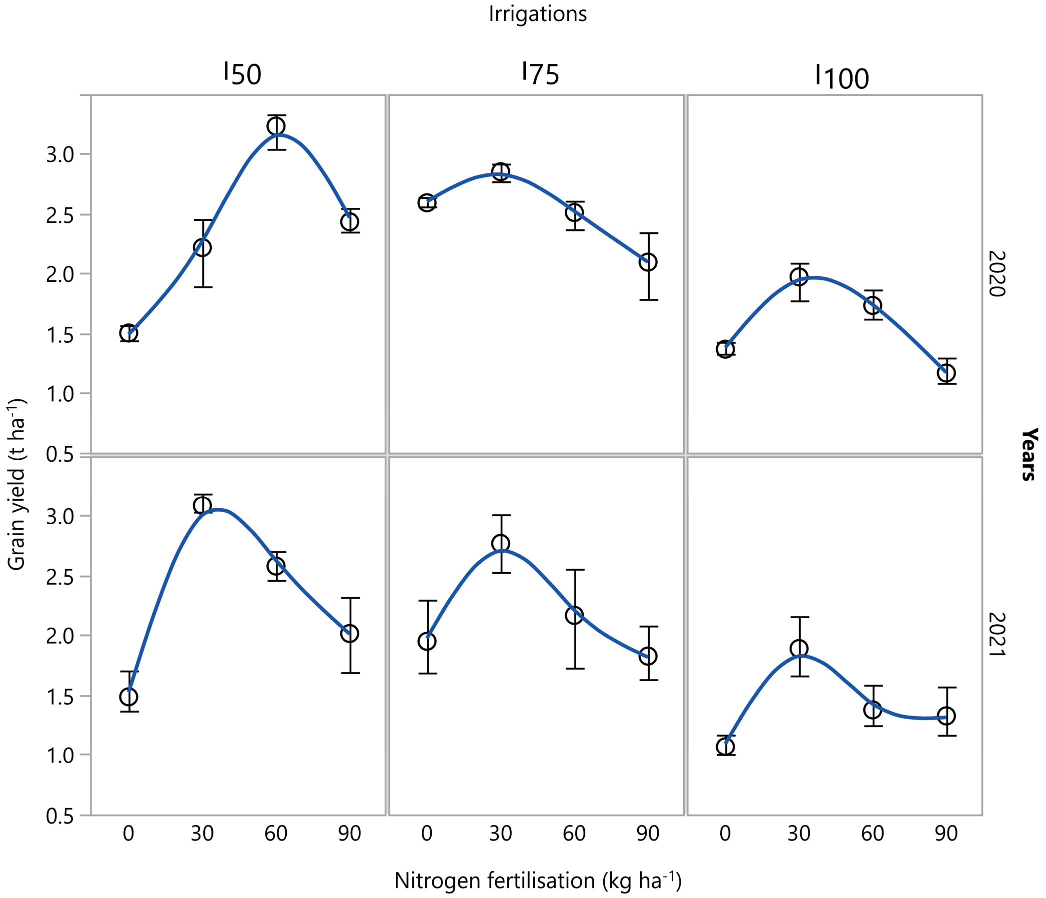

Figure 1. Changes in sesame grain yield according to year, nitrogen dose and irrigation dose.

In general, when all irrigation levels and nitrogen doses are evaluated together over the years, the highest grain yield is achieved at 60 kg ha^{-1} nitrogen dose with I_{50} application in 2020, at 30 kg ha^{-1} nitrogen applications with I_{75} and I_{100} irrigation levels and for all irrigation levels in 2021. The highest grain yields were obtained at a nitrogen dose of 30 kg ha^{-1}. Regarding plant height, the highest heights (170.7 and 160 cm) were obtained for $I_{100}N_{90}$ applications in both trial years (Figure 2). The lowest were obtained for $I_{50}N_0$ applications (129.3 and 109.3 cm). The largest number of plant branches was obtained for the $I_{50}N_{30}$ application (9.3 and 5.7 units) in both years. The lowest number was obtained for the $I_{100}N_0$ application (3.8 and 2.7 units) in both trial years.

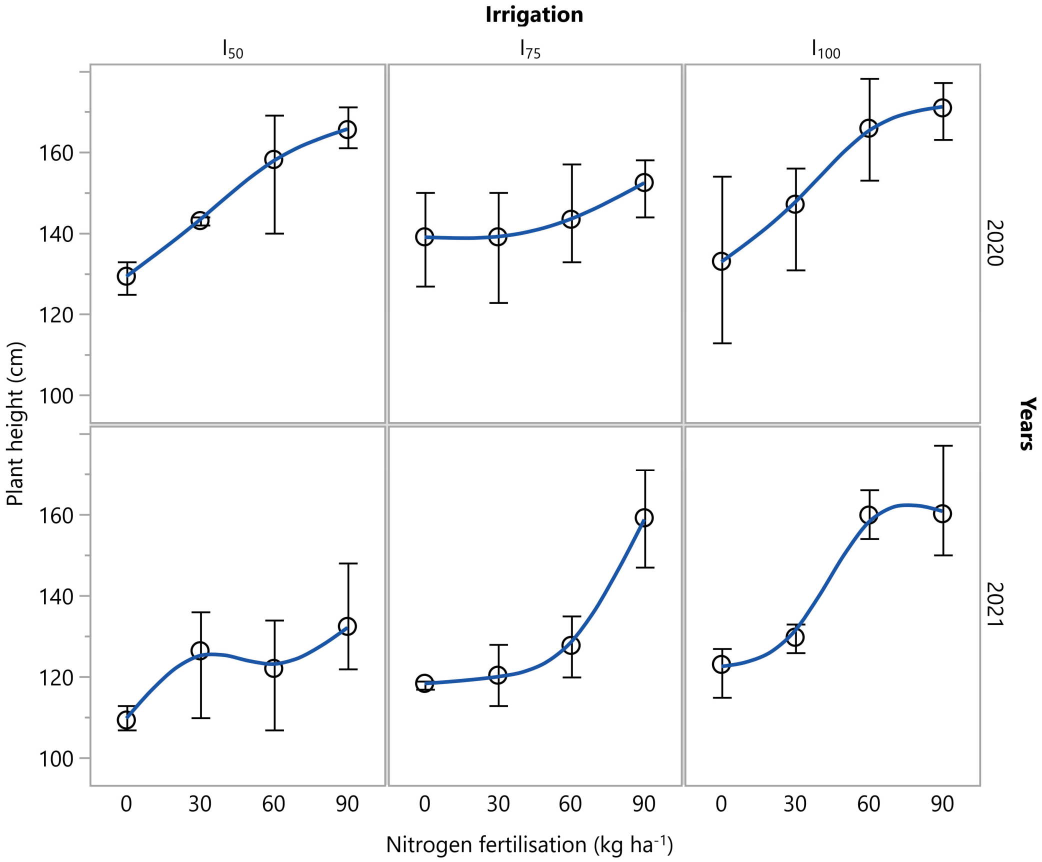

Figure 2. Changes in plant height in sesame according to year, nitrogen dose and irrigation dose.

3.2. Fat Ratio and Fatty Acid Properties

Different irrigation water levels and nitrogen dose applications caused significant changes in sesame's oil content and fatty acid properties (Table 6). Considering the oil content, it can be said that increased irrigation water and nitrogen application caused a decrease in the oil content of sesame (Figure 3). In 2020, the lowest oil content was determined to be 34.61% in the $I_{50}N_{90}$ application, and the highest was 47.13% in the $I_{75}N_0$ application. However, considering the efficiency, the lowest oil content was found for the $I_{100}N_{90}$ treatment and the highest for $I_{50}N_{60}$. In 2021, the lowest was 38.84% for the $I_{50}N_{90}$ application, and the highest was 49.42% for $I_{50}N_{30}$. Considering the efficiency, the lowest oil content was obtained for $I_{100}N_0$ and the highest for $I_{50}N_{60}$, as in 2020.

Table 6. Effect of different nitrogen and water applications on oil ratio and fatty acid content of sesame.

Nitrogen Dose (kg ha^{-1})	Irrigation Water Level	Oil Content (%)	Palmitic (%)	Stearic (%)	Oleic (%)	Elaidic (%)	Linoleic (%)	Arachidic (%)	γ- -Linoleic (%)	Eicodecanixic (%)
					2020					
0	I_{50}	44.95	9.54	5.64	40.46	0.44	43.06	0.24	0.09	0.04
0	I_{75}	47.13	9.69	5.70	40.65	0.45	41.68	0.27	0.14	0.08
0	I_{100}	46.15	8.85	5.39	40.48	0.50	41.66	0.63	0.50	0.30
30	I_{50}	45.95	9.39	5.33	41.13	0.84	41.17	0.77	0.78	0.36
30	I_{75}	44.93	9.13	5.15	41.53	0.54	41.68	0.64	0.25	0.08
30	I_{100}	43.33	9.93	5.94	42.45	0.40	41.44	0.36	1.12	0.30
60	I_{50}	43.15	9.42	5.52	43.35	0.45	39.57	0.72	0.32	0.14
60	I_{75}	44.84	9.14	5.38	41.46	0.36	42.80	0.65	0.17	0.00
60	I_{100}	41.38	9.60	5.60	41.72	0.59	40.93	0.76	0.36	0.22
90	I_{50}	34.61	9.32	5.49	42.98	0.47	39.80	0.69	0.97	0.08
90	I_{75}	43.87	9.31	5.59	43.66	0.90	40.41	0.79	0.39	0.31
90	I_{100}	40.31	9.99	5.96	41.95	0.58	39.67	0.55	0.27	0.20
					2021					
0	I_{50}	48.93	8.46	0.09	43.43	0.37	46.15	0.91	0.04	0.22
0	I_{75}	46.26	8.16	0.11	45.85	0.41	45.28	0.66	0.11	0.2
0	I_{100}	44.15	8.34	0.00	42.97	0.39	46.63	0.00	0.50	0.43
30	I_{50}	49.42	8.83	0.20	43.56	0.42	45.51	0.00	0.03	0.31
30	I_{75}	44.88	7.85	0.00	44.18	0.40	47.13	0.00	0.17	0.38
30	I_{100}	43.74	8.00	0.00	43.52	0.35	46.82	0.00	0.22	0.19
60	I_{50}	42.54	8.10	0.00	45.31	0.38	44.22	0.84	0.33	0.27
60	I_{75}	43.03	8.53	0.17	41.81	0.41	43.42	0.00	0.38	0.28
60	I_{100}	42.18	8.40	0.00	44.64	0.36	45.80	0.00	0.40	0.40
90	I_{50}	38.84	8.87	0.05	46.67	0.39	41.27	1.02	0.2	0.34
90	I_{75}	40.93	8.62	0.00	47.32	0.42	43.63	0.00	0.62	0.43
90	I_{100}	41.44	8.74	0.15	45.00	0.39	44.63	0.00	0.07	0.14
					Means Nitrogen					
0		46.3	8.84	2.82	42.31	0.43	44.08	0.45	0.23	0.21
30		45.4	8.86	2.77	42.73	0.49	43.96	0.29	0.43	0.27
60		42.9	8.86	2.78	43.05	0.43	42.79	0.50	0.33	0.22
90		40.0	9.14	2.87	44.60	0.53	41.57	0.51	0.42	0.25
LSD (0.01)		1.42	0.23	0.09	0.91	ns	0.88	ns	ns	ns
					Means Irrigation					
I_{50}		43.5	8.99	2.79	43.36	0.47	42.59	0.65	0.34	0.22
I_{75}		44.5	8.80	2.76	43.31	0.49	43.25	0.38	0.28	0.22
I_{100}		42.8	8.98	2.88	42.84	0.44	43.45	0.29	0.43	0.27
LSD (0.01)		0.83	0.18	0.13	0.009	0.072	öd	0.003	0.17	0.05

Considering the palmitic content, the lowest value was 8.85% for $I_{100}N_0$, and the highest was 9.99% for $I_{100}N_{90}$. For stearic content, the lowest was 5.15% for $I_{75}N_{30,}$ and the highest was 5.96 for $I_{100}N_{90}$. There was a fluctuation in the oleic fatty acid content due to the effect of the applications (Figure 4). The lowest oleic value was 40.46% for $I_{50}N_{0,}$ and the highest was 43.66% for $I_{75}N_{90}$. For elaidic content, the lowest was 0.36 for the $I_{75}N_{60}$ application, and the highest was 0.90 for $I_{75}N_{90}$. There was a fluctuation in the linoleic fatty acid content for the I_{75} application, as in oleic acid (Figure 5). The lowest linoleic fatty acid value was determined to be 39.57% for the $I_{50}N_{60}$ application, and the highest was 43.06% for the $I_{50}N_0$ application. Regarding arachidic content, the lowest was 0.24% for $I_{50}N_{0,}$ and the highest was 0.79% for $I_{75}N_{90}$. Regarding γ- -linoleic acid content, the $I_{50}N_0$ treatment had the lowest, at 0.09%, and the $I_{100}N_{30}$ application had the highest, at 1.12%. Regarding eicodecanixic fatty acid content, the lowest value was 0 for $I_{75}N_{60,}$ and the highest was 0.36 for $I_{50}N_{30}$.

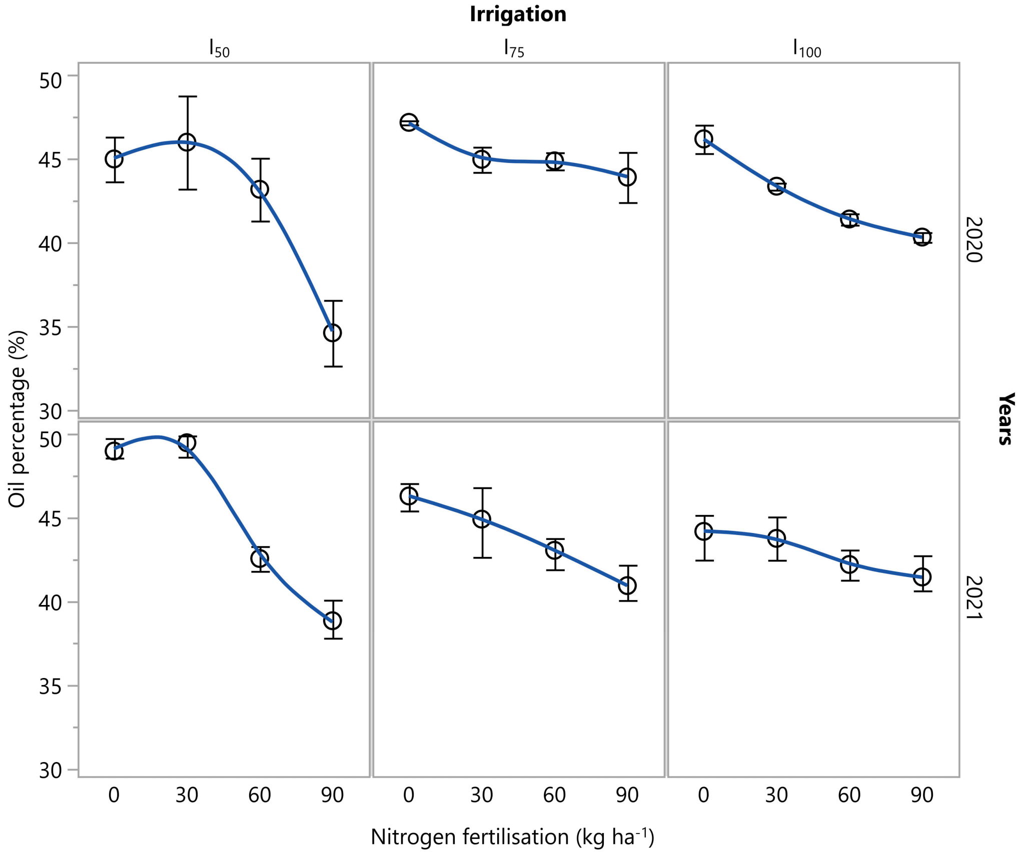

Figure 3. Changes in oil ratio of sesame according to year, nitrogen dose and irrigation dose.

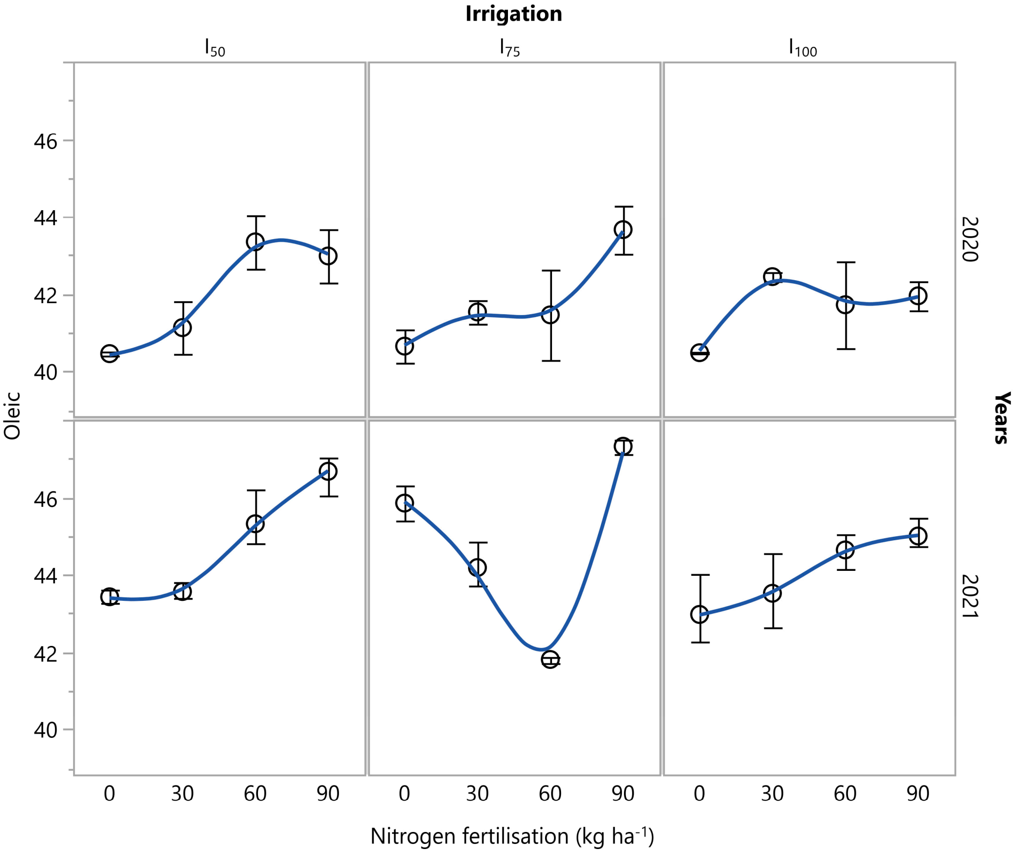

Figure 4. Changes in oleic acid ratio in sesame according to year, nitrogen dose and irrigation dose.

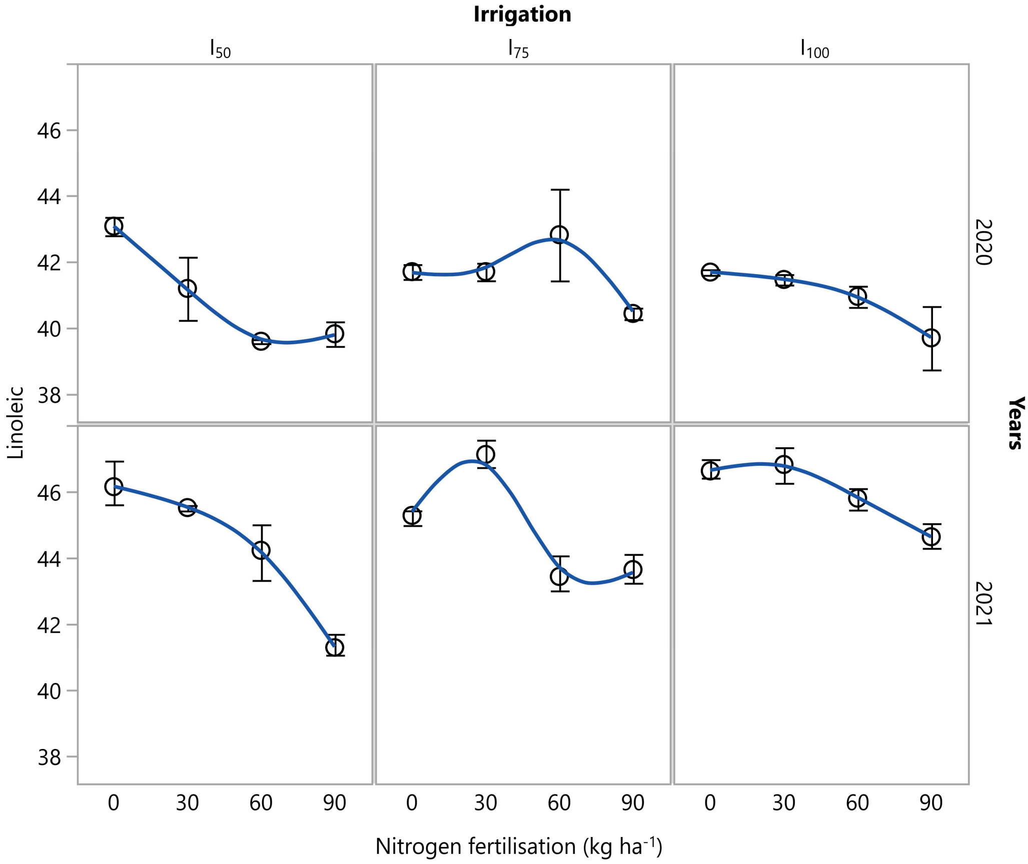

Figure 5. Changes in linoleic acid ratio in sesame according to year, nitrogen dose and irrigation dose.

4. Discussion

4.1. Effect of Irrigation on Sesame Yield

Researchers have reported the effects of irrigation water on sesame yield and quality. The highest yield and seasonal evapotranspiration of sesame, the second product after wheat in the Mediterranean region of Turkey, are 1.67 t ha^{-1} and 465 mm, respectively [35]. Another study conducted in a nearby region with a climate similar to this study was conducted by Bastug et al. [36]. They reported that yield values ranged between 0.46 and 2.06 t ha^{-1}, and seasonal evapotranspiration values ranged between 156 and 519 mm. El Naim and Ahmed [37] stated that different irrigation levels significantly affect yield components (plant height, number of nodes, stem diameter, number of branches) and sesame oil content. Kassab et al. [38] investigated the effects of different irrigation methods (controlled surface irrigation, subsurface drip and surface drip irrigation) and irrigation water levels (100%, 80% and 60% of normal irrigation needs) on growth and yield. They determined that sesame water use efficiency, plant growth and yield characteristics increased at 100% irrigation water level. Sepaskhah and Andam [39], in their research in the Iran-Shiraz region, found the seasonal potential evapotranspiration (ETp) value of sesame to be 910 mm. Ucan et al. [40] reported that the effect of irrigation intervals on sesame yield was nonsignificant and that the Class A pan coefficient of 1.0 can be used for irrigation for maximum plant yield. Tantawy et al. [41], in their study on different sesame varieties in Egypt, found that sesame yield was decreased by up to 6.42% if irrigation was done five times (1.02–1.46 t ha^{-1}) instead of seven times (yield 1.09–1.55 t ha^{-1}). Hassanzadeh et al. [42] conducted a study to determine the response of 27 sesame genotypes to water stress. They stated that water stress decreased chlorophyll A and leaf relative water content (RWC). Eskandari et al. [43] found that all yield characteristics except grain weight were affected by the irrigation regime when evaporation from the Class A evaporation pan reached 150, 200, 250 and 300 mm. Loggale [44] grew two sesame varieties in Sudan under full irrigation, supplementary irrigation and rainfall-based conditions. Statistically ($p < 0.01$) significant results were obtained between plant height, number of capsules per plant, seed size and seed yield (0.832 t ha^{-1} at full irrigation) depending on the irrigation water level, and two to three supplementary irrigations were recommended depending on the drought level.

4.2. Impact of Fertilisation

Using nitrogen fertiliser on sesame causes changes in yield and oil quality. Applying nitrogenous fertiliser according to the growth stages of the plant increases productivity. Adding 46–100 kg·N ha^{-1} in Ethiopian conditions provided maximum yield [10]. N fertiliser rates vary depending on soil, climatic conditions and local agricultural practices [45]. In Nigeria, higher morphological performance and seed yield (1333.3 kg ha^{-1}) were obtained by applying 46 kg·N ha^{-1} [46]. Another study increased the N application rate from 20 to 80 kg·N ha^{-1} and observed a steady increase in yield [47]. Applying 123 kg·N ha^{-1} and 60 kg·P ha^{-1} in China provided maximum economic returns [48]. In Sudan, sesame provided a higher net yield with 60 kg·N ha^{-1} and 30 kg·P ha^{-1}, and a higher sesame seed yield (769 kg ha^{-1}) was obtained when 44 kg·N ha^{-1} was applied. On the other hand, a five-year study claimed that a higher sesame yield (706 kg ha^{-1}) was recorded at an application rate of 75 kg·N ha^{-1} [49]. Applying 142 kg ha^{-1}·N in Egypt was found to be economical for sesame production [50]. In Sudan, Bahar et al. [51] found that an application rate of 100 kg·N ha^{-1} provided higher seed yield. The difference in the amount of nitrogen fertiliser recommended between these studies is due to the nutrients present in the soil, the climate of the region, differences in sesame varieties and differences in the regions' ecologies.

The most important quality parameters of sesame are the amount of oil and the quality of the oil. Both parameters are directly affected by irrigation and nitrogen applications. Oleic and linoleic acids are unsaturated fatty acids, and sesame oil with higher amounts of these acids is preferred for health [13]. These two acids (oleic and linoleic acids) account for more than 80% of total acids. Previous studies reported that sesame's oleic and linoleic acid contents ranged from 36.9 to 51.6% and from 27.5 to 49.1%, respectively, depending on the varieties and irrigation practices [52–57]. From this perspective, the results obtained in the study are similar to those of the literature. The desired primary fatty acid composition for sesame seeds should be high in oleic acid and low in linoleic acid among unsaturated fatty acids, low in palmitic acid and high in stearic acid among saturated fatty acids. The Muganlı-57 variety has the highest amount of oleic acid and stearic acid among the varieties grown in Turkey [36]. Were et al. [54] reported that some African sesame varieties' oil and fatty acid contents changed significantly between the trial years. In contrast, the erucic acid content did not change during the trial years. Among the fatty acids in sesame, oleic, linoleic, palmitic and stearic are the main components, accounting for 98% of the total fatty acids. They also concluded that fat content was negatively correlated with palmitic and linoleic acids and positively correlated with stearic and oleic acids. Sesame oil content and composition depend on genotype-water stress level. Oleic, linoleic and linolenic acids are healthy unsaturated fatty acids [57]. Water deficit practices affect sesame oil yield [58–60]. Limiting irrigation water rates reduces the oil percentage of sesame [61]. Additionally, according to their study, Laribi et al. [62] found that the palmitic acid content increased under limited irrigation conditions. According to Ozkan and Kulak [58], oleic acid content decreased with increasing water deficiency practices. According to the results of these studies, palmitic acid content varied between 8.66 and 9.34%, oleic acid content varied between 39.75 and 44.21% and linoleic acid content varied between 39.85 and 44.27%. The differences between these studies were the environmental and growing conditions. Under abiotic stress conditions, parameters related to plant behaviour and biosynthesis of bioactive compounds may change [62,63].

5. Conclusions

This study assessed changes in grain yield and quality characteristics of sesame, whose production in arid and semi-arid regions often depends on rainfall. The effects of applying different nitrogen rates and different irrigation levels were investigated. The results of this experiment provide valuable information for practitioners that can contribute to increasing sesame productivity. The main conclusions of the study are:

1. While increasing the amount of irrigation water caused a decrease in yield, increasing the nitrogen dose (up to 60 kg N ha^{-1}) first increased the yield, but a decrease occurred in the next dose (90 kg N ha^{-1}). Considering the yield obtained from the subjects and the oil amounts calculated from this yield, the best application is $I_{50}N_{60}$ (50% of Epan and a dose of 60 kg N ha^{-1}) (Table 5). In other words, the highest yield was obtained for $I_{50}N_{60}$ in both research years (3.2 tons ha^{-1} in 2020 and 3.1 tons ha^{-1} in 2021). In general, increasing water and nitrogen doses caused a decrease in sesame oil content.

2. Increasing the nitrogen dose caused an increase in oleic acid content and a decrease in linoleic acid content. The amount of irrigation water also showed an effect opposite to nitrogen doses. Increasing the irrigation water amount caused a decrease in oleic acid content and an increase in linoleic acid content. The highest oleic acid content (43.06%) was achieved for the $I_{75}N_{90}$ treatment. In the case of linoleic fatty acid, the greatest value (43.66%) was for the $I_{50}N_0$ treatment.

3. It was observed that increasing water and nitrogen application caused a decrease in sesame oil.

4. In the experiment, WUE values in the range of 0.20 to 0.87 kg ha^{-1} m^{-3} and IWUE values between 0.22 and 1.24 kg ha^{-1} m^{-3} were obtained for all treatments.

5. Depending on the treatment, the EWP was 0.41–2.80 \$ m^{-3}, and the B/C ratio was 0.94–3.84.

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