Turkish Journal of Agriculture and Forestry

Volume 48 | Number 2 Article 8

4-1-2024

Enhancing grain yield, oil content, fatty acid composition and changes in antioxidant properties of camelina using Wi-Fi radiation

Maryam Khashayarfard

Sedigheh Arbabian

Danial KAHRIZI

Fariba Sharifnia

Recommended Citation

Khashayarfard, Maryam; Arbabian, Sedigheh; KAHRIZI, Danial; and Sharifnia, Fariba (2024) "Enhancing grain yield, oil content, fatty acid composition and changes in antioxidant properties of camelina using Wi-Fi radiation," *Turkish Journal of Agriculture and Forestry*: Vol. 48: No. 2, Article 8. https://doi.org/10.55730/1300-011X.3178

Available at: https://journals.tubitak.gov.tr/agriculture/vol48/iss2/8

Turkish Journal of Agriculture and Forestry

http://journals.tubitak.gov.tr/agriculture/

Research Article

Turk J Agric For
(2024) 48: 250-262
© TÜBİTAK
doi:10.55730/1300-011X.3178

Enhancing grain yield, oil content, fatty acid composition and changes in antioxidant properties of Camelina *sativa* L. using Wi-Fi radiation

Maryam KHASHAYARFARD[1], **Sedigheh ARBABIAN**[1], **Danial KAHRIZI**[2,*], **Fariba SHARIFNIA**[1]

[1]Department of Biology, North Tehran Branch, Islamic Azad University, Tehran, Iran

[2]Department of Agricultural Biotechnology, Faculty of Agriculture, Tarbiat Modares University, Tehran, Iran

Received: 30.11.2023 • **Accepted/Published Online:** 02.05.2024 • **Final Version:** 01.04.2024

Abstract: Exposure to electromagnetic radiation (ER) in the radio frequency is one of the most common and rapidly growing environmental factors affecting human. Therefore, given the increasing global growth of telecommunication towers and Wi-Fi waves, understanding the potential of positive or negative effects of Wi-Fi electromagnetic waves (WEW) on the quality and quantity parameters of plants is essential. An experiment was carried out during the years 2020–2021 at the Research Farm of Tarbiat Modares University to investigate the effect of WEW on grain yield, fatty acid composition (FA), oil content, and antioxidant properties of camelina. Seeds were subjected to Wi-Fi electromagnetic radiation at distances of 15 cm (ER15) and 25 cm (ER25) from the modem for 24 h. The results showed that electromagnetic waves significantly affected grain yield , increasing it by approximately 23.45%. Additionally, the amount of oil and protein, crucial components of camelina seeds, exhibited a respective increase of 6.91% and decrease of 2.9% under Wi-Fi radiation conditions. Total tocopherol decreased by 6.39%, while β-T remained unaffected by Wi-Fi radiation. Furthermore, the quantity of sterols (brassicasterol, cholesterol, and campesterol) decreased significantly due to Wi-Fi radiation. Based on the fatty acid profile responses, the maximum content of polyunsaturated fatty acids (ΣPUFA) was obtained in ER15 treatment, representing an increase of approximately 1.62%. Consequently, these waves resulted in a decrease in saturated fatty acids (ΣSFA) and erucic acid, thereby increasing the quality of camelina oil. In conclusion, WEW pretreatment has potential to increase grain yield, oil percentage, and quality of camelina oil.

Key words: Wi-Fi, camelina, grain yield, protein content, oil content, fatty acid

1. Introduction

Today, many agricultural lands are exposed to radio frequencies, and farmers allow the installation of telecommunication towers on agricultural land due to the modest financial benefits of agriculture (Upadhyaya et al., 2022). Wi-Fi refers to any system that uses the IEEE 802.11 standard and was developed by the Institute of Electrical and Electronics Engineers (IEEE) (Ishak et al., 2011). Wi-Fi technology employs radio waves for communication, primarily in the frequency range of 2.400 to 2.484 GHz and 5.150 to 5.825 GHz (IEEE, 2016). According to researchers, Wi-Fi waves and other wireless electromagnetic fields produce pulsed waves that are usually much more biologically active than nonpulsed electromagnetic waves with the same frequency and mean wave intensity, leading to biological effects in living organisms (Van Boxem et al., 2014; Pall, 2015; Panagopoulos et al., 2015). Reports indicate that electromagnetic waves strongly affect plants (Saleh et al., 2020). One of these effects is the thermal effect of electromagnetic waves, which can be easily absorbed by plants and cause physiological and metabolic changes, resulting in final changes in cell metabolism (Kovacs and Keresztes, 2002; Kaur et al., 2021; Rivero et al., 2022). If the amount of thermal energy exceeds the capacity of the plant to absorb, it may increase the thermal load of the plant's organs and the entire organism (Kovacs and Keresztes, 2002; 2017; Rivero et al., 2022). Additionally, oils are among the compounds that undergo oxidation during heating. Reactive oxygen species are produced during heating with microwave electromagnetic waves, making oils prone to oxidation under microwave heating conditions compared to standard heat (Borges et al., 2015; Kishimoto, 2019).

Camelina (*Camelina sativa* L. Crantz), a dicotyledonous plant, is an industrial oilseed crop belonging to the Brassicaceae family (Vollmann and Eynck, 2015; Righini et al., 2019; Gore and Kurt, 2021). It possesses numerous

* Correspondence: dkahrizi@modares.ac.ir

properties and uses, including industry, nutrition, and health. The unique characteristics of camelina oil's fatty acids have given it high industrial and food value. (Berti et al., 2016; Ghobadi et al., 2021). High levels of essential fatty acids and natural antioxidants give camelina seeds highly nutritious. These compounds include polyunsaturated fatty acids, phenolic compounds, tocopherols, vitamins, phospholipids, and phytosterols (Krzyżaniak et al., 2019; Estakhr and Ranjbar, 2021; Ghamarnia et al., 2022). Camelina oil consists of approximately 50% of PUFA, with alpha-linolenic acid (omega-3 (ω-3)) comprising approximately 28%–50%, and linoleic acid (omega-3 (ω-3)) comprising approximately 15%–23% of the total fatty acids (Krzyżaniak et al., 2019; Kurasiak-Popowska et al., 2019; Kurasiak-Popowska and Stuper-Szablewska, 2019; Zając et al., 2020). The concentration of tocopherols in camelina oil ranges from 55.6 to 99.4 mg/100 g (Hrastar et al., 2012; Zubr and Matthäus, 2002; Rahman et al., 2018), and the concentration of sterols ranges from 360 to 590 mg/100 g (Belayneh et al., 2018; Marszałkiewicz et al., 2017). Among tocopherols, gamma-tocopherol is the most dominant, comprising approximately 90% (Abramovič et al. 2007). Furthermore, these compositions not only contribute to antioxidant activity but also affect the taste and color of the oil (Kurasiak-Popowska et al. 2019). Also, camelina seed is one of the strongest biological antioxidants towing to its high alpha-tocopherol content in vitamin E, requiring no additives for shelf life (Rostami Ahmadvandi et al., 2021; Rostami Ahmadvandi and Faghihi, 2021). Additionally, the protein content of camelina seed ranges from approximately24.5% to 31.7%, rich in essential amino acids with high biological value, including leucine, valine, lysine, phenylalanine, and isoleucine (Bătrîna et al. 2020).

Several studies showed that free radicals produced by electromagnetic waves cause the process of lipid peroxidation in living organisms (Mahato et al., 2022). Recent studies have further indicated that electromagnetic waves affect the esterification reaction, which is required for the formation of fatty acids and biodiesel production in oil palm (*Elaeis guineensis*) (Yeong et al., 2019) and soybean (*Glycine max*) (Nguyen et al. , 2020).

According to the literature cited, camelina has abundant reserves of FA, particularly ω-3 and ω-6, which play a crucial role in providing human food security. Conversely, numerous natural antioxidants stabilize oils and protect unsaturated fatty acids from oxidation. Nevertheless, studies on the effect of Wi-Fi electromagnetic wave treatment on grain yield and oil quality of camelina remain limited. Therefore, our focus in this study is to enhance grain yield, oil content, fatty acid composition, and changes in antioxidant properties of camelina through Wi-Fi radiation.

2. Materials and methods

2.1. Treatments and plant materials

Camelina seeds (Soheil cultivar) were obtained from Biston Shafa Co. (Kermanshah, Iran). To treat them with Wi-Fi electromagnetic waves, a Mobin Net Modem HUAWEI B612s_25d was used. One group of seeds was exposed to electromagnetic radiation (ER) at a distance of 15 cm (ER15), while another group was positioned at a distance of 25 cm (ER25) from the modem (Mobin Net modem HUAWEI B612s_25d) for a duration of 24 h.

2.2. Farm operations

The irradiated seeds were cultivated in November 2020 at the research farm of the Faculty of Agriculture, Tarbiat Modares University, Tehran, Iran, (35º44'N, 51º09'E, and 1265 masl). Each experimental unit was considered 3.70 m in length and 1.2 m in width, with a row distance of 50 cm. Control and treated seeds (ER15 and ER25) were planted in three rows, with a targeted sowing depth of 0.5 cm. At the 2–4 leaf stage, excess seedlings were thinned. To control the weeds, the plots and the distance between them were manually weeded twice during the growing season.

2.3. Site characterization

As shown in Table 1, a composite sample of soil from a depth of 0–30 cm was prepared and sent to the soil laboratory to determine soil properties at the experimental site.

Based on the coupon classification system, the test site has a dry and semiarid climate (Peel et al., 2007). Meteorological parameters, including minimum and maximum air temperature (ºC) and rainfall (mm), were collected by the Chitgar weather station (35 º 44' N, 51 º 10' E and 1260 masl) (Figure).

2.4. Data measurements

2.4.1. Grain yield

To determine the camelina grain yield, a 2.0 m^2 area of each plot was harvested at physiological maturity (BBCH: 89; Martinelli and Galasso, 2011), and the grain was subsequently separated from the threshed and weighed.

2.4.2. Protein content

First, the nitrogen value in the seeds was measured using a spectrophotometer via the indophenol blue method. Subsequently, the protein content was determined by multiplying the nitrogen value by 6.26 (Novamsky et al., 1974).

2.4.3. Oil content

The oil content measurement method was Soxhlet extraction. Initially, 5 g of ground and dried seeds were placed into paper extraction. Subsequently, the seed oils were extracted using 200 mL of n-hexane for 11 h at 60 °C.

2.4.4. Tocopherols and sterols

The camelina seed samples were ground, and the oil from each sample was separately extracted using the Soxhlet

Table 1. Soil properties from experimental field (depth of 0–30 cm) before camelina planting during the 2020–2021 growing season.

Soil texture	Clay	Sand	Loam	pH	EC[†]	O.C	OM	TN	P	K
(%)					(dS/m)	(%)			(mg kg^{-1})	
Sandy loam	10	74	16	7.3	0.90	0.85	1.385	0.15	35	475

[†]Electrical conductivity (EC); organic carbon (OC); organic matter (OM); total nitrogen (TN).

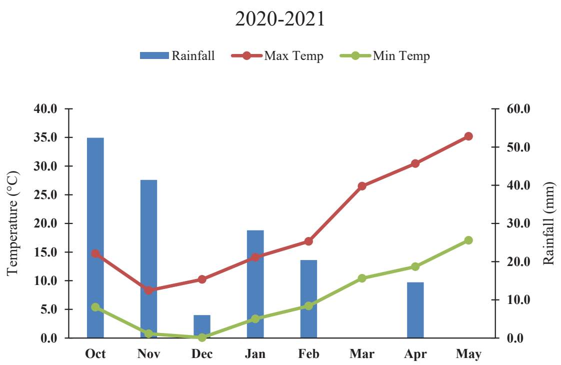

Figure. Maximum, minimum temperatures and rainfall at the Chitgar Station, Tehran during 2020–2021 growing season.

method with petroleum ether solvent for 4 h. The resulting oil was then stored in clean, dark glass containers for quality measurements.

The identification and determination of tocopherols in the oil was conducted using high-performance liquid chromatography (HPLC) in accordance with the AOCS standard Ce8-89 (Firestone, 1994).

The identification of sterols extracted from oil was performed in accordance with AOAC standard no. 51/970, using a gas chromatography (GC) device equipped with a flame detector. A 30-m HP5 capillary column with an inner diameter of 0.25 mm was employed and maintained at a column temperature of 250 °C. The injection site temperature, detector temperature, and injection volume were set at 250 °C, 280 °C, and 1 µL, respectively (Firestone, 1997).

2.4.5. Fatty acid extraction

To determine the composition of FAs through gas chromatography (GC), samples underwent analysis at Techno Azma Company using a SHIMADZU machine (model Nexis 2030), equipped with a 60-m column and an internal diameter of 0.25 mm. The detector of the device was FID, and the capillary column was Dikmacap-2330. The temperature of the injection site and detector was set to 250 °C and 260 °C, respectively. Additionally, the injection volume was 1 µL, and the splitting ratio of the device was set to 1:60. Hydrogen gas with a purity of 99.99% and a flow rate of 2 mL/min was used as the carrier gas. The device's temperature program was configured such that the initial temperature of 60 °C was maintained for 2 min. The temperature increased at a gradient of 10 °C per minute until reaching 200 °C. Subsequently, with a gradient of 5 °C per minute, it reached a temperature of 240 °C and remained at this temperature for 7 min because there was enough time for all the FAs to leave the column. The identification of FAs was determined by comparing their inhibition time with that of pure standard FAs, and the results were expressed as a percentage.

2.5. Statistical analysis

The data were analyzed using SAS (version 9.3) based on one-way ANOVA (SAS-Institute, Cary, NC, USA, 1985). All data were expressed as the mean and standard error (SE) of the values. Mean comparisons were examined using the least significant difference (LSD) at $p < 0.05$. Pearson correlation was also performed between the data.

3. Results

3.1. Grain yield

The data presented in Table 2 clearly indicate that the Wi-Fi electromagnetic treatments had a significant effect ($p < 0.01$) on grain yield. Specifically, the ER15 treatment resulted in the highest grain yield compared to the control plants. However, both ER15 and ER25 treatments increased grain yield by 23.45% and 9.59%, respectively, compared to the control plants (Table 3).

Table 2. Analysis of variance for grain yield and seed quality affected by Wi-Fi electromagnetic waves on camelina.

S.O.V	df	GY	OC	PC	Tocopherols					Sterols			
					α-T	β-T	γ-T	σ-T	Total T	Brass	Chol	Camp	β-Sit
Block	2	13992.16	0.11	1.37	0.36	0.04	63.40	0.52	61.88	7.20	10.11	244.24	664.33
Treat	2	31395.20**	0.90**	2.24**	0.18*	0.01^{ns}	9.81*	0.06*	14.76**	20.67**	14.12*	123.23*	1.00^{ns}
Error	4	1497.68	0.0.5	0.04	0.02	0.02	0.55	0.03	0.51	1.01	0.94	7.87	183.83
Total	8												
CV (%)		4.02	2.18	0.84	11.99	13.22	1.08	4.15	3.41	3.18	6.18	3.18	6.18

GY: grain yield; OC: oil content; PC: protein content; α-T: α-tocopherol; β-T: β-tocopherol; γ-T: γ-tocopherol; σ-T: σ-tocopherol; Total T: total tocopherol; Brass: brassicasterol; Chol: cholesterol; Camp: campesterol; β-Sit: β-sitosterol.
ns, * and ** show nonsignificant and significant differences at ($p < 0.05$), and ($p < 0.01$) levels of significance, respectively.

Table 3. Effect of Wi-Fi electromagnetic waves on tocopherols and sterols of camelina.

Exposure distance	GY[†] (kg/h)	OC (%)	PC (%)	α-T (mg/100 g)	γ-T (mg/100 g)	σ-T (mg/100 g)	Total T (mg/100 g)	Brass (mg/100 g)	Chol (mg/100 g)	Camp (mg/100 g)
Control	867.1 ± 59.8^{b}	36.91 ± 0.12^{b}	24.88 ± 0.30^{a}	1.61 ± 0.27^{a}	65.16 ± 2.46^{a}	1.58 ± 0.24^{a}	68.50 ± 2.50^{a}	26.95 ± 0.81^{a}	30.66 ± 1.20^{a}	94.33 ± 4.09^{a}
15 cm	1070.5 ± 35.1^{a}	37.43 ± 0.99^{a}	23.16 ± 0.44^{c}	1.11 ± 0.11^{b}	61.60 ± 2.95^{b}	1.30 ± 0.22^{b}	64.12 ± 2.83^{b}	21.71 ± 1.19^{c}	26.32 ± 0.66^{b}	81.52 ± 6.25^{b}
25 cm	950.3 ± 29.9^{b}	37.58 ± 0.20^{b}	23.83 ± 0.44^{b}	1.35 ± 0.23^{ab}	62.82 ± 2.59^{b}	1.40 ± 0.25^{b}	65.71 ± 2.57^{b}	24.00 ± 1.00^{b}	28.33 ± 1.45^{b}	88.33 ± 5.54^{a}

[†] GY: grain yield; OC: oil content; PC: protein content; α-T: α-tocopherol; β-T: β-tocopherol; γ-T: γ-tocopherol; σ-T: σ-tocopherol; Total T: total tocopherol; Brass: brassicasterol; Chol: cholesterol; Camp: campesterol.
Each column (mean ± SE) with common letters shows nonsignificant differences ($p < 0.05$) according to LSD test.

3.2. Oil content

The oil content significantly increased under Wi-Fi electromagnetic exposure compared to the control plants (Table 2). The highest oil content, 37.99%, was observed under ER15, representing a 2.9% increase compared to the control plants (Table 3).

3.3. Protein content

According to Table 2, Wi-Fi electromagnetic treatments are significantly effective ($p < 0.01$) in improving protein content. Wi-Fi electromagnetic decreased protein content to the lowest levels, reported as 6.91% in the ER15 treatment and 4.22% in the ER25 treatment, compared to the control plants (Table 3).

3.4. Tocopherols and sterols

Analysis of variance showed that the impact of Wi-Fi electromagnetic radiation on α-tocopherol content was significant ($p < 0.05$) (Table 2). The highest α-tocopherol content was observed in the control group, while the lowest content was observed at a distance of 15 cm from the exposure source (ER15), indicating a decrease of approximately 28% compared with the control (Table 3). According to Table 2, the γ-tocopherol content of camelina was significantly affected by Wi-Fi electromagnetic radiation ($p < 0.05$). The γ-tocopherol content decreased by 5.5% and 3.6% under Wi-Fi electromagnetic radiation compared to the control, respectively (Table 3). The results indicated that the σ-tocopherol was affected by Wi-Fi electromagnetic treatments ($p < 0.05$) (Table 2). Moreover, in nonirradiated conditions (control), the highest concentration of σ-tocopherol was observed. The Wi-Fi electromagnetic waves at 15 and 25 cm decreased the σ-tocopherol content by approximately 17.7% and 11.4%, respectively. However, no significant statistical difference was observed between radiation treatments (Table 3). Analysis of variances revealed a significant effect of Wi-Fi electromagnetic radiation on total tocopherol levels ($p < 0.01$) (Table 2). The highest total tocopherol content was observed under nonirradiated conditions (control). Mean comparison indicated a significant decrease in total tocopherol in camelina seeds exposed to Wi-Fi electromagnetic radiation, by approximately 4%–6% (Table 3).

The effect of Wi-Fi electromagnetic radiation on brassicasterol concentration was found to be significant ($p < 0.01$) (Table 2). The minimum values of these traits were recorded in plants treated with ER15 and ER25, exhibiting approximately 19.4% and 10.9% reduction compared to the control, respectively (Table 3). The obtained results indicate that both ER15 and ER25 treatments led to a significant decrease in cholesterol content in camelina seeds (Table 2). The lowest cholesterol content in seeds was obtained for the 15 and 25 cm treatments, showing approximately 14% and 8% reductions compared to the control (Table 3). According to the results, both ER15 and ER25 treatments significantly decreased the campesterol content in camelina seeds (Table 2). Furthermore, the campesterol content of the seeds decreased with the increased Wi-Fi radiation. The highest and lowest campesterol content was observed in the control and the 15 cm treatment, respectively, with approximately a 13.5% reduction compared to the control. Additionally, there was no significant difference in campesterol content between the 25 cm treated and control plants (Table 3).

3.5. Fatty acid composition

According to the results (Table 4), the effect of WEW on myristic acid was significant ($p < 0.01$). Approaching the source of wave radiation (ER15) led to a 33% decrease in the content of myristic acid compared with the control condition (Table 5). A significant difference in stearic acid content was observed in the electromagnetic wave radiation ($p < 0.05$) (Table 4). In the conditions of Wi-Fi radiation, the treatment with ER15 resulted in an approximately 6.55% increase in stearic acid compared to the control, while ER25 showed no statistically significant difference from the control (Table 5). Analysis of the obtained results indicated a significant difference in oleic acid content due to electromagnetic wave radiation ($p < 0.01$) (Table 4). The results indicated that the proximity of camelina seeds to the radiation source leads to a significant decrease in the percentage of oleic acid, with the lowest levels observed in the ER15 treatment (Table 5). Additionally, a significant difference in eicosanoic acid content was observed in electromagnetic wave radiation ($p < 0.01$) (Table 4). Exposing the seeds to the radiation source at a distance of 15 cm resulted in a significant increase in oleic acid content by approximately 1.89% (Table 5). The erucic acid level was significantly affected by Wi-Fi radiation treatments ($p < 0.01$) (Table 4). Additionally, the content of erucic acid decreased by approximately 3.21 as the seeds were closer to the Wi-Fi radiation source (ER15) (Table 5). According to the findings, linoleic acid was significantly affected by electromagnetic waves (Table 4). The treatments employed led to a significant decrease in linoleic acid compared to the control, with the ER15 treatment exhibiting a more significant effect on decreasing this fatty acid (Table 5). Our results clearly showed that the effect of Wi-Fi waves on the linolenic acid content was significant ($p < 0.05$) (Table 4). The highest amount of linolenic acid was obtained in the ER15 treatment (approximately 2.58%), and subsequently, the ER25 treatment had the most significant effect in increasing this fatty acid (Table 5). The composition of saturated fatty acids (SFAs) and polyunsaturated fatty acids (PUFAs) was significantly affected by electromagnetic waves, while monounsaturated fatty acids (MUFAs) remained unaffected by these conditions. The highest amount of ∑PUFA was observed in the ER15 treatment, exhibiting an increase compared to the control. Additionally, pertaining to the ∑SFA, the ER15 led to a significant decrease (1.47%) compared to the control (Table 5).

3.6. Correlation of tocopherols and sterols

According to the results presented in Table 6, a positive correlation was observed between total T and both γ-T ($r = 1.00^{**}$) and α-T ($r = 0.92^{**}$). Additionally, a negative and significant correlation was found between total tocopherol and σ-T ($r = -0.65^{**}$). Moreover, a positive and significant correlation was detected between α-T and γ-T ($r = 0.89^{**}$). Among the sterols components of camelina seed oil, the highest correlation reported was between cholesterol (Chol) and campesterol (Camp) ($r = 0.92^{**}$). Generally, no significant correlation was observed among other sterol components. Furthermore, the highest positive and significant correlation between tocopherol and sterol components was observed in Camp with total T ($r = 0.97^{**}$), γ-T ($r = 0.95^{**}$), and α-T ($r = 0.90^{**}$).

Table 4. Analysis of variance for FAs affected by Wi-Fi electromagnetic waves on camelina.

S.O.V	df	FA composition														
		MA†	PA	SA	BA	ArA	OA	EA	ErA	NrA	LA	LiA	EdA	∑PUFA	∑MUFA	∑SFA
Block	2	0.08	0.07	0.02	0.03	0.003	0.02	0.92	0.02	4.07	0.01	0.11	0.03	0.21	1.30	0.08
Treatment	2	0.09^{**}	0.02^{ns}	0.02^{*}	0.00^{ns}	0.01^{ns}	0.08^{**}	0.03^{**}	0.01^{**}	4.40^{ns}	0.02^{**}	0.33^{*}	0.00^{ns}	0.18^{*}	4.40^{ns}	0.01^{*}
Error	4	0.01	0.01	0.01	0.008	0.003	0.004	0.001	0.00	4.40	0. 01	0.04	0.00	0.04	4.24	0.001
Total	8															
CV	-	4.08	0.09	1.45	1.42	0.80	0.15	0.21	0.39	1.43	0.18	0.66	1.42	0.40	6.02	0.35

†MA: myristic acid; PA: palmitic acid; SA: stearic acid; BA: behenic acid; ArA: arachidic acid; OA: oleic acid; EA: eicosanoic acid; ErA: erucic acid; NrA: nervonic acid; LA: linoleic acid; LiA: linoleic acid; EdA: eicosadienoic acid; ∑PUFA: polyunsaturated fatty acids; ∑MUFA: monounsaturated fatty acids; ∑SFA: saturated fatty acids.

ns, * and ** show nonsignificant and significant differences at ($p < 0.05$), and ($p < 0.01$) levels of significance, respectively.

Table 5. Effect of Wi-Fi electromagnetic waves on fatty acid composition (%) of camelina.

Exposure distance	MA†	SA	OA	EA	ErA	LA	LiA	∑PUFA	∑SFA
Control	0.12 ± 0.01^{a}	2.29 ± 0.02^{b}	13.82 ± 0.05^{a}	14.78 ± 0.33^{c}	4.04 ± 0.05^{a}	17.63 ± 0.04^{a}	32.14 ± 0.10b	51.85 ± 0.13b	11.52 ± 0.08a
15 cm	0.08 ± 0.00^{b}	2.44 ± 0.03^{a}	13.71 ± 0.03^{b}	15.07 ± 0.31^{a}	3.91 ± 0.04^{c}	17.45 ± 0.02^{c}	32.97 ± 0.17a	52.32 ± 0.22a	11.35 ± 0.09b
25 cm	0.09 ± 0.00^{b}	2.32 ± 0.01^{b}	13.80 ± 0.02^{a}	14.99 ± 0.31^{b}	4.00 ± 0.04^{b}	17.55 ± 0.06^{b}	32.33 ± 0.16ab	51.95 ± 0.18b	11.38 ± 0.11b

†MA: myristic acid; PA: palmitic acid; SA: stearic acid; BA: behenic acid; ArA: arachidic acid; OA: oleic acid; EA: eicosanoic acid; ErA: erucic acid; LA: linoleic acid; LiA: linoleic acid; ∑PUFA: polyunsaturated fatty acids; ∑SFA: saturated fatty acids. Each column (mean ± SE) with common letters shows nonsignificantly differences ($p < 0.05$) according to LSD test.

Table 6. Pearson correlation coefficients among tocopherols and sterols in camelina affected by Wi-Fi electromagnetic waves.

	α-T	β-T	γ-T	σ-T	Total T	Brass	Chol	Camp	Sito
α-T	1								
β-T	0.17^{ns}	1							
γ-T	0.89^{**}	0.06^{ns}	1						
σ-T	-0.53^{ns}	0.35^{ns}	-0.70^{**}	1					
Total T	0.92^{**}	0.11^{ns}	1.00^{**}	-0.65^{**}	1				
Brass	0.37^{ns}	0.88^{**}	0.27^{ns}	0.20^{ns}	0.32^{ns}	1			
Chol	0.94^{**}	0.40^{ns}	0.84^{**}	-0.31^{ns}	0.88^{**}	0.56^{ns}	1		
Camp	0.90^{**}	0.34^{ns}	0.95^{**}	-0.55^{ns}	0.97^{**}	0.53^{ns}	0.92^{**}	1	
Sito	0.06^{ns}	0.11^{ns}	-0.18^{ns}	-0.14^{ns}	-0.19^{ns}	0.25^{ns}	-0.06^{ns}	-0.12^{ns}	1

α-T: α-tocopherol; β-T: β-tocopherol; γ-T: γ-tocopherol; σ-T: σ-tocopherol; Total T: total tocopherol; Brass: brassicasterol; Chol: cholesterol; Camp: campesterol; β-Sito: β-sitosterol.
ns, * and ** show nonsignificant and significant differences at ($p < 0.05$), and ($p < 0.01$) levels of significance, respectively.

3.7. Correlation of fatty acid composition

The results listed in Table 7 showed a significant positive correlation between linolenic acid and PUFA ($r = 0.95^{**}$). Additionally, a negative correlation was observed between linolenic acid and both oleic acid ($r = -0.78^{**}$) and erucic acid ($r = -0.76^{**}$). However, no positive correlation was observed between PUFA and linoleic acid ($r = -0.18^{ns}$), and similarly, the correlation between PUFA and oleic acid was negative and significant ($r = -0.76^{*}$). In addition, no significant correlation was observed between MUFA and essential fatty acids, such as oleic, linoleic, linolenic, and eicosanoic acid. However, based on the results, SFA was significantly correlated with palmitic acid ($r = 0.89^{**}$).

4. Discussion

4.1. Grain yield

Our study evaluated various parameters of camelina seed quantity and quality in response to different electromagnetic waves. The result of this study shows that grain yield has significantly increased under Wi-Fi electromagnetic. Indeed, electromagnetic waves induce changes in various metabolic activities (such as the Krebs cycle and chlorophyll content) and gene expression in plants (Vian et al., 2016). The application of low-frequency electromagnetic waves increases the final grain yield of camelina. Additionally, seed pretreatment with such waves positively impact plant growth and grain yield (Pietruszewski et al., 2007). Furthermore, long-term exposure to Wi-Fi waves can induce genetic mutations and metabolic changes that might result in changes to vegetation growth and reproduction (Ahloowalia and Maluszynski, 2001; Sharma et al., 2017). According to our study, using a microwave device for seed treatment before planting increases the yield of rapeseed, camelina, and mustard by 10 to 15% (Bastron et al., 2020). Previously, the effect of magnetic waves on improving the growth of wheat (Katsenios et al., 2016; Cecchett et al., 2022) and soybean yield (Baghel et al., 2018) has been reported.

4.2. Oil content

Electromagnetic radiation causes oxidative stress and dysfunction of cells through lipid peroxidation, subsequently leading to the accumulation of hydrogen peroxide (Sharma et al., 2009; Chandel et al., 2017). Generally, electromagnetic waves penetrate oil-containing seeds, inducing interactions within the seeds and converting electromagnetic energy into heat through two

Table 7. Pearson correlation coefficients among fatty acid profile in camelina affected by Wi-Fi electromagnetic waves.

	MA	PA	SA	OA	LA	ALA	ArA	EA	EDA	BA	ErA	NA	PUFA	MUFA	SFA
MA[†]	1														
PA	-0.21^{ns}	1													
SA	-0.50^{ns}	0.35^{ns}	1												
OA	0.90^{**}	-0.52^{ns}	-0.53^{ns}	1											
LA	0.67^{*}	0.47^{ns}	-0.44^{ns}	0.43^{ns}	1										
ALA	-0.67^{*}	0.46^{ns}	0.76^{*}	-0.78^{**}	-0.44^{ns}	1									
ArA	0.21^{ns}	-0.31^{ns}	0.33^{ns}	0.14^{ns}	-0.23^{ns}	0.14^{ns}	1								
EA	0.53^{ns}	-0.17^{ns}	0.16^{ns}	0.62^{ns}	0.17^{ns}	-0.05^{ns}	0.32^{ns}	1							
EdA	-0.66^{*}	0.42^{ns}	0.24^{ns}	-0.75^{*}	-0.29^{ns}	0.45^{ns}	-0.51^{ns}	-0.70^{*}	1						
BA	-0.47^{ns}	0.31^{ns}	0.00^{ns}	-0.57^{ns}	-0.02^{ns}	0.19^{ns}	0.09^{ns}	-0.58^{ns}	0.15^{ns}	1					
ErA	0.46^{ns}	-0.78^{*}	-0.82^{**}	0.62^{ns}	0.01^{ns}	-0.76^{*}	-0.02^{ns}	-0.08^{ns}	-0.29^{ns}	-0.22^{ns}	1				
NA	0.01^{ns}	0.36^{ns}	-0.33^{ns}	-0.21^{ns}	0.32^{ns}	-0.08^{ns}	-0.36^{ns}	-0.48^{ns}	0.32^{ns}	0.30^{ns}	-0.01^{ns}	1			
PUFA	-0.56^{ns}	0.68^{ns}	0.68^{*}	-0.764^{*}	-0.18^{ns}	0.95^{**}	0.02^{ns}	-0.07^{ns}	0.49^{ns}	0.21^{ns}	-0.83^{**}	0.04^{ns}	1		
MUFA	0.21^{ns}	0.29^{ns}	-0.38^{ns}	-0.00^{ns}	0.42^{ns}	-0.17^{ns}	-0.31^{ns}	-0.25^{ns}	0.13^{ns}	0.14^{ns}	0.04^{ns}	0.96^{**}	-0.04^{ns}	1	
SFA	-0.27^{ns}	0.89^{**}	0.69^{*}	-0.55^{ns}	0.22^{ns}	0.65^{ns}	0.06^{ns}	-0.00^{ns}	0.29^{ns}	0.28^{ns}	-0.93^{**}	0.11^{ns}	0.78^{*}	0.05^{ns}	1

[†] MA: myristic acid; PA: palmitic acid; SA: stearic acid; BA: behenic acid; ArA: arachidic acid; OA: oleic acid; EA: eicosanoic acid; ErA: erucic acid; NrA: nervonic acid; LA: linoleic acid; LiA: linoleic acid; EdA: eicosadienoic acid; ∑PUFA: polyunsaturated fatty acids; ∑MUFA: monounsaturated fatty acids; ∑SFA: saturated fatty acids.

ns, * and ** show nonsignificant and significant differences at ($p < 0.05$) and ($p < 0.01$) levels of significance, respectively.

mechanisms: dipole polarization and ionic conduction (Anwar et al., 2015; Franco et al., 2015). The heat from electromagnetic waves increases the temperature of biological materials, particularly those associated with the cell membrane (Banik et al., 2003; Tkalec et al., 2005; Vian et al., 2016). To maintain optimal membrane viscosity for normal cell function, plants adapt their lipid membrane composition in response to environmental temperature changes, thereby maintaining optimal membrane fluidity. (Rawat et al., 2021, Yu et al., 2021). In the present study, WEW treatment enhanced the oil content in camelina plants compared to the control. Previous studies have shown that microwave irradiation improves oil yield (Ghafoor et al., 2019; Karrar et al., 2020; Mazaheri et al., 2019). Furthermore, electromagnetic waves have been used to improve the oil quality in oilseed crops (Koubaa et al., 2016). Based on our study, conducted on rapeseed (Azadmard-Damirchi et al., 2010) and corn (Afzal et al., 2015), we found that microwave and magnetic field waves increase the oil yield and oil content, respectively.

4.3. Protein content

Based on the results, the protein content was approximately 4.22%–6.91% lower in plants exposed to WEW than in control plants. This observation could be attributed to the role of the electromagnetic fields in changing physiological processes, such as respiration, photosynthesis, and nutrient absorption, as well as in biochemical characteristics, including changes in enzyme activity, protein levels, and secondary metabolites (Hafeez et al., 2023). Also, the radiation emitted from mobile phones reduces protein synthesis and increases membrane damage and the activity of antioxidant enzymes (Afzal and Mansoor, 2012). On the other hand, since there is a negative relationship between protein and oil storage in the seed (Jasinski et al., 2018), our study suggests that an increasing in oil percentage is associated with a decrease in protein content. In our study, as microwave irradiation increased in rice plants, the protein content decreased (Zhao et al., 2007). Additionally, protein solubility increased during short-term microwave application but decreased with longer treatment durations (Ashraf et al., 2012).

4.4. Tocopherols and sterols

The composition of tocopherols and sterols in oilseed crops decreases with heating and storage; hence, the storage conditions after harvesting seeds are crucial (Ying et al., 2018; Zaunschirm et al., 2018). Researchers have studied the effect of microwave irradiation as a heat pretreatment on the value of tocopherols and phytosterols in oil, as well as their effect on oxidative stability in rapeseed plants (Azadmard-Damirchi et al., 2010; Yang et al., 2013; Wroniak et al., 2016). The results of our study were consistent with those of Wroniak et al. (2016), who revealed a significant reduction in the levels of α-T and γ-T after expose to microwaves for 3 min. Additionally, Azadmard-Damirchi et al. (2010) reported that with the increase in the exposure time of canola seeds to microwaves, the content of α-T and γ-T decreases. The concentration of tocopherols and sterols significantly affects the nutritional value and stability of oils. . Specifically, tocopherols play a crucial biochemical role in protecting PUFA against peroxidation. The highest amount of biological activity is related to alpha-tocopherol (Ying et al., 2018; Zaunschirm et al., 2018). Other studies reported that the total tocopherol content of camelina oil to be in the range of 55.8 to 99.4 mg/100 g (Zubr and Mätthaus, 2002; Hrastar et al, 2012; Marszałkiewicz et al., 2017; Ratusz et al., 2018), which is consistent with our findings (Table 3). According to the reports of Ratusz et al. (2018), γ-tocopherol (γ-T) predominated in all analyzed camelina oils, comprising more than 90%, which aligns with the results of our study. In the study by Ratusz et al. (2018), the γ-T content ranged from 52.41 to 72.30 mg/100 g, consistent with the findings of Hrastar et al. (2012) and Marszałkiewicz et al. (2017), who showed that γ-T has the most dominance (more than 90%) in the studied oils. Additionally, α-T, δ-T, and β-T have been found in the composition of camelina oil, with respective values of 0.95–2.78, 0.62–2.05, and 0.09–0.28 mg/100 g (Ratusz et al., 2018). Our study revealed significant positive correlations between total T and both γ-T ($r = 1.00^{**}$) and α-T ($r = 0.92^{**}$) (Table 6).

Phytosterols, which are mainly found in seed oil, are important components of oil with antioxidant properties (Sujith Kumar et al., 2017). They additionally exhibit cholesterol-lowering effects (Belayneh et al., 2015; Marszałkiewicz et al., 2017; Ying et al., 2018). Pretreatment of oilseeds at high temperatures results in the degradation of phytosterols, thereby significantly affecting their properties during extraction. Since electromagnetic waves create a thermal effect on plant tissues, they can affect the final composition of sterols. According to the results of our study, sterols showed a significant decrease under WEW conditions (Table 3). In various research studies on camelina oil composition, sterol content is commonly found between 193 and 590 mg/100 g (Günç Ergönül et al., 2018; Rahman et al., 2018). Additionally, campesterol, β-sitosterol, and stigmasterol are generally found in high levels in plant oils. Previous studies by Ratusz et al. (2018) showed that the major sterols in the camelina oils were β-sitosterol (167–262 mg/100 g) and campesterol (74–112 mg/100 g). Our study confirmed these findings. In our study, the relatively strong relationships between Camp and Chol ($r = 0.92^{**}$) was observed and also Camp had a strong positive correlation with total T ($r = 0.97^{**}$), γ-T ($r = 0.95^{**}$), and α-T ($r = 0.90^{**}$) (Table 6). The cholesterol levels ranged from 25 to 33 mg/100 g, consistent with the findings of Marszałkiewicz et al. (2017).

4.5. Fatty acid composition

In the present study, the FA composition of camelina (Table 4) was consistent with multiple reports in the research on camelina fatty acids (Krzyżaniak et al., 2019; Kurasiak-Popowska et al., 2019; Kurasiak-Popowska and Stuper-Szablewska, 2019; Zając et al., 2020). Electromagnetic waves induce oxidative stress in plants, leading to the production of ROS in various tissues such as cell membranes, resulting in lipid peroxidation and affecting the quantity and quality of fatty acids (Chandel et al., 2017; Mahato et al., 2022). Based on the results, pretreatment with WEW affects the FAs composition of camelina seeds. Similar to our study, Suri et al. (2020) observed a significant difference in the FA composition of camelina oil between untreated and treated plants with electromagnetic waves. Several studies have examined the effect of electromagnetic wave treatment on changing the fatty acid composition of peanut (*Arachis hypogaea* L) (Yoshida et al., 2005), sunflower (*Heliantus annuus* L.) (Anjum et al., 2006), pumpkin (*Cucurbita spp*) (Yoshida et al., 2006), and camellia (*Camellia oleifera* Abel.) (Ye et al., 2021). Among the fatty acid composition, linolenic acid (C18:3) and linoleic acid (C18:2) are the critical fatty acids of camelina. These acids serve as precursors for omega-6 (ω-6) and omega-3 (ω-3) fatty acids. Given that the human body cannot synthesize ω-6 and ω-3 and their reserves are limited, increasing these compounds in plants assumes greater significance (Watts et al., 2016). The results indicate that the 15 cm treatment distance (ER15) increased the linolenic acid content (Table 5), ultimately increasing the quality of camelina oil. Additionally, our study revealed a strong correlation between linolenic acid and PUFA ($r = 0.95^{**}$). Similar to our study, Uquiche et al. (2008) reported an increase in the quality of hazelnut oil (*Gevuina avellana* Mol) due to microwave electromagnetic radiation. Furthermore, Sharaf-Eldin (2015) observed a positive effect of electromagnetic waves on the fatty acid composition of artichoke seeds (*Cynara curriculum*), specifically noting a significant increase in linolenic acid content among the essential fatty acids.

The results indicated that when the samples were exposed to electromagnetic waves, oleic and linoleic acid content decreased significantly (Table 5). This finding aligns with previous studies on hazelnut oil by Uquiche et al. (2008). Additionally, Ghafoor et al. (2019) observed that microwave radiation reduces linoleic acid content in poppy seed oil (*Papaver somniferum*). Additionally, the results revealed that a negative correlation was observed between linolenic acid and both oleic acid ($r = -0.78^{**}$) and erucic acid ($r = -0.76^{**}$). This finding aligns with the study conducted by Soorni et al. (2022), which also reported a negative correlation between linolenic acid and erucic acid. Our results indicated a significant increase in ∑PUFA composition under both wave treatments, while ∑SUFA composition decreased under these conditions (Table 5). Wroniak et al. (2016) reported that no significant changes were observed in the composition percentages of MUFAs, PUFAs, and SFAs in rapeseed under microwave electromagnetic treatment. Another study on Chinese cabbage (*Brassica campestris* L.) showed that the composition of ∑PUFA increased under UV-B wave stress (Tripathi and Agrawal, 2016).

5. Conclusion

Most studies conducted on the effects of Wi-Fi electromagnetic waves emphasize either their harmful or beneficial effects on the health of living beings. Our study showed that Wi-Fi electromagnetic waves significantly increased the grain yield and the percentage of camelina oil, while also increasing the oil's quality by increasing the content of linolenic acid, eicosanoic acid, and ∑PUFA, which are critical components of camelina oil. Additionally, these waves have a positive effect on reducing harmful erucic acid and ∑SFA. This finding provides the basis for further research aimed at reducing this fatty acid through the radiation of electromagnetic wave radiation, thereby improving the nutritional properties of camelina oil.

Acknowledgment

We would like to express our sincere appreciation to the Research Deputy of Islamic Azad University, North Tehran Branch, for their financial support and technical assistance throughout this research.

Conflict of interest

The authors declare that they have no conflict of interest.

References

Abramovič H, Butinar B, Nikolič V (2007). Changes occurring in phenolic content, tocopherol composition and oxidative stability of Camelina sativa oil during storage. Food Chemistry 104 (3): 903-909. https://doi.org/10.1016/j.foodchem.2006.12.044

Afzal I, Noor MA, Bakhtavar MA, Ahmad A, Haq Z (2015). Improvement of spring maize performance through physical and physiological seed enhancements. Seed Science and Technology 43 (2): 238-249. https://doi.org/10.15258/sst.2015.43.2.02

Afzal M, Mansoor S (2012). Effect of mobile phone radiations on morphological and biochemical parameters of Mung bean (Vigna radiata) and wheat (Triticum aestivum) seedlings. Asian Journal of Agriculture 4 (2): 149-152.

Ahloowalia BS, Maluszynski M (2001). Induced mutations–A new paradigm in plant breeding. Euphytica 118: 167-173. https://doi.org/10.1023/A:1004162323428

Albi T, Lanzón A, Guinda A, Leon M, Pérez-Camino MC (1997). Microwave and conventional heating effects on their oxidative degradation of edible fats. Journal of Agriculture Food Chemistry 45: 3795-3798. https://doi.org/10.1021/jf970181x

Anjum F, Anwar F, Jamil A, Iqbal M (2006). Microwave roasting effects on the physico-chemical composition and oxidative stability of sunflower seed oil. Journal of American Oils Chemists Society 83: 777-784. https://doi.org/10.1007/s11746-006-5014-1

Anwar J, Shafique U, Rehman R, Salman M, Dar A et al. (2015). Microwave chemistry: Effect of ions on dielectric heating in microwave ovens. Arabian Journal of Chemistry 8 (1): 100-104. https://doi.org/10.1016/j.arabjc.2011.01.014

Ashraf S, Saeed SMG, Sayeed SA, Ali R (2012). Impact of Microwave Treatment on the Functionality of Cereals and Legumes. International Journal of Agriculture and Biology 14 (3): 356-370.

Azadmard-Damirchi S, Habibi-Nodeh F, Hesari J, andNemati M, Achachlouei BF (2010). Effect of pretreatment with microwaves on oxidative stability and nutraceuticals content of oil from rapeseed. Food Chemistry 121 (4): 1211-1215. https://doi.org/10.1016/j.foodchem.2010.02.006

Baghel L, Kataria S, Guruprasad KN (2018). Effect of static magnetic field pretreatment on growth, photosynthetic performance and yield of soybean under water stress. Photosynthetica 56: 718–730. https://doi.org/10.1007/s11099-017-0722-3.

Bătrîna ȘL, Jurcoan, ȘT, Popescu IU, Marin FL, Imbrea IM et al. (2020). Camelina sativa: a study on amino acid content. Biotechnology Letters 25 (1): 1136-1142. https://doi: 10.25083/rbl/25.1/1136.1142

Banik S, Bandyopadhyay S, Ganguly S (2003). Bioeffects of microwave––a brief review. Bioresource Technology 87 (2): 155-159. https://doi.org/10.1016/S0960-8524(02)00169-4

Bastron AV, Filimonova NG, Meshcheryakov AV, Mikheeva NB, Ermakova IN (2020). Technology of microwave treatment of camelina seeds and its economic efficiency. In IOP Conference Series: Journal of Earth and Environmental Sciences 421 (2): 022065. https://doi.10.1088/1755-1315/421/2/022065

Belayneh HD, Wehling RL, Cahoon E, Ciftci ON (2015). Extraction of omega-3-rich oil from Camelina sativa seed using supercritical carbon dioxide. Journal of Supercritical Fluids 104: 153–159. https://doi.org/10.1016/j.supflu.2015.06.002/

Berti M, Gesch R, Eynck C, Anderson J, Cermak S (2016). Camelina uses, genetics, genomics, production, and management. Industrial Crops and Products 94: 690-710. https://doi.org/10.1016/j.indcrop.2016.09.034

Borges TH, Malheiro R, de Souza AM, Casal S, Pereira JA (2015). Microwave heating induces changes in the physicochemical properties of baru (Dipteryx alata Vog.) and soybean crude oils. Journal of Lipid Science and Technology 117 (4): 503-513. https://doi.org/10.1002/ejlt.201400351

Chandel S, Kaur S, Singh HP, Batish DR, Kohli RK (2017). Exposure to 2100 MHz electromagnetic field radiations induces reactive oxygen species generation in Allium cepa roots. Journal of Microscopy and Ultrastructure 5 (4): 225-229. https://doi.org/10.1016/j.jmau.2017.09.001

Cecchetti D, Pawełek A, Wyszkowska J, Antoszewski M, Szmidt-Jaworska A (2022). Treatment of Winter Wheat (Triticum aestivum L.) Seeds with Electromagnetic Field Influences Germination and Phytohormone Balance Depending on Seed Size. Agronomy 12 (6): 1423. https://doi.org/10.3390/agronomy12061423.

Efthimiadou A, Katsenios N, Karkanis A, Papastylianou P, Triantafyllidis V et al. (2014). Effects of presowing pulsed electromagnetic treatment of tomato seed on growth, yield, and lycopene content. Scientific World Journal 369745. https://doi.org/10.1155/2014/369745

Estakhr A, Ranjbar G (2021). The Preliminary Study of Camelina Compatibility as a New Oil Crop in the Temperate Region of Fars Province. Agrotechniques in Industrial Crops 1 (2): 77-84. https://doi 10.22126/atic.2021.6525.1017

Firestone D (1994). Official Methods & Recommended Practices of the American Oil Chemists´ Society, (4th ed), AOCS Press, Champaign, IL, USA.

Firestone D (1997). Official Methods of Analysis of the Association of Official Analytical Chemists, (17th ed.), Arlington, USA.

Franco AP, Yamamoto LY, Tadini CC, Gut JAW (2015). Dielectric properties of green coconut water relevant to microwave processing: effect of temperature and field frequency. Journal of Food Engineering 155: 69-78. https://doi.org/10.1016/j.jfoodeng.2015.01.011

Ghafoor K, Özcan MM, Fahad AJ, Babiker EE, Fadimu GJ (2019). Changes in quality, bioactive compounds, fatty acids, tocopherols, and phenolic composition in oven-and microwave-roasted poppy seeds and oil. Food Science and Technology 99: 490-496. https://doi.org/10.1016/j.lwt.2018.10.017

Ghamarnia H, Palash M, Dousti B (2022). Camelina Zoning for Different Climate Conditions in Kurdistan Province. Agrotech Ind Crops 2 (1): 49-56. https:// doi: 10.22126/atic.2022.7903.1056

Ghobadi R, Rostami Ahmadvandi H, Zeinodini A, Akbarabadi A (2021). Nutritional Properties and Benefits of Camelina Oil and Meal. Agrotechniques in Industrial Crops 1 (2): 71-76. https://doi: 10.22126/atic.2021.6441.1009

Gore M, Kurt O (2021). Evaluation of Camelina (Camelina sativa) Genotypes Grown in Winter at Different Sowing Dates in Northern Turkey Ecological Conditions in Terms of Yield and Oil Ratio. Agrotechniques in Industrial Crops 1 (4): 154-159. https://doi: 10.22126/atic.2022.7231.1032

Guy SO, Wysocki DJ, Schillinger WF, Chastain TG, Karow RS et al. (2014). Camelina: adaptation and performance of genotypes. Field Crops Research 155: 224-232. https://doi.org/10.1016/j.fcr.2013.09.002

Günç Ergönül P, Aksoylu Özbek Z (2018). Identification of bioactive compounds and total phenol contents of cold pressed oils from safflower and camelina seeds. Journal of Food Measurement and Characterization 12: 2313-2323. https://doi.org/10.1007/s11694-018-9848-7

Hafeez MB, Zahra N, Ahmad N, Shi Z, Raza A et al. (2023). Growth, physiological, biochemical and molecular changes in plants induced by magnetic fields: a review. Plant Biology 25(1): 8-23. https://doi.org/10.1111/plb.13459

Halgamuge MN (2017). Weak radiofrequency radiation exposure from mobile phone radiation on plants. Electromagnetic Biology and Medicine 36: 213-235. https://doi.org/10.1080/15368378.2016.1220389

Hrastar R, Abramovič H, Košir IJ (2012). In situ quality evaluation of Camelina sativa landrace. European Journal of Lipid Science and Technology 114 (3): 343-351. https://doi.org/10.1002/ejlt.201100003

IEEE (2016). IEEE Standard for Information Technology—-telecommunications and information exchange between systems Local and metropolitan area networks—specific requirements – Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) Specifications. IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012), pp. 1–3534.

Ishak NH, Ariffin R, Ali A, Sagiruddin MA, Tawi FMT (2011). Biological effects of Wi-fi electromagnetic radiation. Proceedings, 2011 IEEE International Conference on Control System, Computing and Engineering, ICCSCE. 551-556. https://doi 10.1109/ICCSCE.2011.6190587

ISTA (2008). International rules for seed testing: edition 2008. The International Seed Testing Association (ISTA).

Jasinski S, Chardon F, Nesi N, Lécureuil A, Guerche P (2018). Improving seed oil and protein content in Brassicaceae: some new genetic insights from Arabidopsis thaliana. OCL 25 (6): p.D603. https://doi.org/10.1051/ocl/2018047

Juodka R, Nainienė R, Juškienė V, Juška R, Leikus R et al. (2022). Camelina (Camelina sativa (L.) Crantz) as feedstuffs in meat type poultry diet: A source of protein and n-3 fatty acids. Animals 12 (3): 295. https://doi.org/10.3390/ani12030295

Karrar E, Sheth S, Wei W, Wang X (2020). Effect of microwave heating on lipid composition, oxidative stability, color value, chemical properties, and antioxidant activity of gurum (Citrulluslanatus var. Colocynthoide) seed oil. Biocatalysis and Agricultural Biotechnology 23: 101504. https://doi.org/10.1016/j.bcab.2020.101504

Katsenios N, Bilalis D, Efthimiadou A, Aivalakis G, Nikolopoulou AE et al. (2016). Role of pulsed electromagnetic field on enzyme activity, germination, plant growth and yield of durum wheat. Biocatalysis and Agricultural Biotechnology 6: 152-158. https://doi.org/10.1016/j.bcab.2016.03.010

Kaur S, Vian A, Chandel S, Singh HP, Batish DR et al. (2021). Sensitivity of plants to high frequency electromagnetic radiation: cellular mechanisms and morphological changes. Reviews in Environmental Science and Bio/Technology 20 (1): 55-74. https://doi.org/10.1007/s11157-020-09563-9

Kishimoto N (2019). Microwave heating induces oxidative degradation of extra virgin olive oil. Food Science and Technology Research 25 (1): 75-79. https://doi.org/10.3136/fstr.25.75

Koubaa M, Mhemdi H, Barba FJ, Roohinejad S, Greiner R et al. (2016). Oilseed treatment by ultrasounds and microwaves to improve oil yield and quality: an overview. Food Research International 85: 59-66. https://doi.org/10.1016/j.foodres.2016.04.007

Kovacs E, Keresztes A (2002). Effect of gamma and UV-B/C radiation on plant cells. Micron 33 (2): 199-210. https://doi.org/10.1016/S0968-4328(01)00012-9

Krzyżaniak M, Stolarski MJ, Tworkowski J, Puttick D, Eynck C et al. (2019). Yield and seed composition of 10 spring camelina genotypes cultivated in the temperate climate of Central Europe. Industrial Crops and Products 138: 111443. https://doi.org/10.1016/j.indcrop.2019.06.006

Kurasiak-Popowska D, Ryńska B, Stuper-Szablewska K (2019). Analysis of distribution of selected bioactive compounds in Camelina sativa from seeds to pomace and oil. Agronomy 9 (4): 168. https://doi.org/10.3390/agronomy9040168

Mahato S, Sun DW, Zhu Z (2022). Ca2+ ATPase Enzyme Activities and Lipid and Protein Oxidations of Grass Carp (Ctenopharyngodon Idellus) Stored at 4oC for 30 min under Electromagnetic Fields. Food Chemistry 133914. https://doi.org/10.1016/j.foodchem.2022.133914

Marszałkiewicz S, Siger A, Kubzdela ER, Ratusz K, Rudzińska M (2017). Fizyczno-chemiczne właściwości olejów lniankowych tłoczonych na zimno. Nauka Przyroda Technologie 11 (3): 22. https://doi.10.17306/J.NPT.2017.3.22

Martinelli T, Galasso I (2011). Phenological growth stages of Camelina sativa according to the extended BBCH scale. Annals of Applied Biology 158: 87-94. https://doi.org/10.1111/j.1744-7348.2010.00444.x

Mazaheri Y, Torbati M, Azadmard-Damirchi S, Savage GP (2019). Effect of roasting and microwave pre-treatments of Nigella sativa L. seeds on lipase activity and the quality of the oil. Food Chemistry 274: 480-486. https://doi.org/10.1016/j.foodchem.2018.09.001

Menegatti RD, de Oliveira LO, da Costa ÁVL, Braga EJB, Bianchi VJ (2019). Magnetic field and gibberelic acid as pre-germination treatments of passion fruit seeds. Revista Ciencia Agronomica 17 (1): 15-22. https://doi.org/10.28998/rca.v17i1.6522

Neupane D, Solomon JKQ, Davison J, Lawry T (2018). Nitrogen source and rate effects on grain and potential biodiesel production of camelina in the semiarid environment of northern Nevada. Gcb Bioenergy 10: 861-876. https://doi.org/10.1111/gcbb.12540

Neupane D, Solomon JKQ, Mclennon E, Davison J, Lawry T (2019). Sowing date and sowing method influence on camelina cultivars grain yield, oil concentration, and biodiesel production. Food and Energy Security e00166. https://doi.org/10.1002/fes3.166

Nguyen HC, Lee HY, Su CH, Shih WJ, Chien CC (2020). Green process for fatty acid production from soybean oil through microwave-mediated autocatalytic synthesis. Chemical Engineering and Processing 147: 107782. https://doi.org/10.1016/j.cep.2019.107782

Novamsky I, Van Eck R, Van Schouwenburg CH, Walinga I (1974). Total nitrogen determination in plant material by means of the indophenol-blue method. Netherlands Journal of Agricultural Science 22: 3-5. https://doi.org/10.18174/njas.v22i1.17230

Pall ML (2015). Scientific evidence contradicts findings and assumptions of Canadian Safety Panel 6: microwaves act through voltage-gated calcium channel activation to induce biological impacts at non-thermal levels, supporting a paradigm shift for microwave/lower frequency electromagnetic field action. Reviews on Environmental Health 3: 99-116. ttps://doi.org/10.1515/reveh-2015-0001

Panagopoulos DJ, Johansson O, Carlo GL (2015). Real versus simulated mobile phone exposures in experimental studies (article ID 607053, 8 pages). BioMed. Res. Int. https://doi.org/10.1155/2015/607053

Peel MC, Finlayson BL, McMahon TA (2007). Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences 11: 1633-1644. https://doi.org/10.5194/hess-11-1633-2007

Pietruszewski S, Muszynski S, Dziwulska A (2007). Electromagnetic fields and electromagnetic radiation as non-invasive external stimulants for seeds [selected methods and responses]. International Agrophysics 21 (1): 95-100.

Rahman MJ, Ambigaipalan P, Shahidi F (2018). Biological activities of camelina and sophia seeds phenolics: inhibition of LDL oxidation, DNA damage, and pancreatic lipase and α-glucosidase activities. Journal of Food Science 83 (1): 237-245. https://doi.org/10.1111/1750-3841.14007

Ratusz K, Popis E, Ciemniewska-Żytkiewicz H, Wroniak M (2016). Oxidative stability of camelina (Camelina sativa L.) oil using pressure differential scanning calorimetry and Rancimat method. Journal of Thermal Analysis and Calorimetry 126: 343-351. https://doi.org/10.1007/s10973-016-5642-0

Ratusz K, Symoniuk E, Wroniak M, Rudzińska M (2018). Bioactive compounds, nutritional quality and oxidative stability of cold-pressed camelina (Camelina sativa L.) oils. Applied Sciences 8 (12): 2606. https://doi.org/10.3390/app8122606

Rawat N, Singla-Pareek SL, Pareek A (2021). Membrane dynamics during individual and combined abiotic stresses in plants and tools to study the same. Physiologia Plantarum 171 (4): 653-676. https://doi.org/10.1111/ppl.13217

Righini D, Zanetti F, Martínez-Force E, Mandrioli M, Toschi TG et al. (2019). Shifting sowing of camelina from spring to autumn enhances the oil quality for bio-based applications in response to temperature and seed carbon stock. Industrial Crops and Products 137: 66-73. https://doi.org/10.1016/j.indcrop.2019.05.009

Rivero RM, Mittler R, Blumwald E, Zandalinas SI (2022). Developing climate-resilient crops: improving plant tolerance to stress combination. Plant Journal 109 (2): 373-389. https:// doi: 10.1111/tpj.15483

Rostami Ahmadvandi H, Faghihi A (2021). Adapted Oilseed Crops with the Ability to Grow Economically in Dryland Conditions in Iran. Agrotechniques in Industrial Crops 1 (3): 122-128. https://doi: 10.22126/atic.2021.6518.1015

Rostami Ahmadvandi H, Zeinodini A, Ghobadi R, Gore, M (2021). Benefits of Adding Camelina to Rainfed Crop Rotation in Iran: A Crop with High Drought Tolerance. Agrotechniques in Industrial Crops 1 (2): 91-96. https://doi: 10.22126/atic.2021.6410.1007

Saleh RF, Al-Sugmiany RZ, Al-Doori MM, Al-Azzawie A (2020). Phenotypic and Genetic Effects of Wi-Fi Waves on Some Bacterial Species Isolated from Otitis Media Infection Tropical. Journal of Natural Products 4 (12): 1056-1063. https://doi.org/10.26538/tjnpr/v4i12. 6

SAS-Institute (1985). SAS User's Guide: Statistics, 5th ed. SAS Institute Inc, Cary, NC.

Sharaf-Eldin MA (2015). Electromagnetic treatments of cardoon seeds affect plant growth and linoleic acid content. In: IX International Symposium on Artichoke, Cardoon and Their Wild Relatives 1147 2015 Sep 29: 399-406. https://doi.10.17660/ActaHortic.2016.1147.56

Sharma S, Chatterjee S, Kataria S, Joshi J, Datta S et al. (2017). A review on responses of plants to UV-B radiation related stress. UV-B Radiation: From Environmental Stressor to Regulator of Plant Growth 75-97. https://doi.org/10.1002/9781119143611.ch5

Sharma VP, Singh HP, Kohli RK, Batish DR (2009). Mobile phone radiation inhibits Vigna radiata (mung bean) root growth by inducing oxidative stress. Science of The Total Environment 407 (21): 5543-5547. https://doi.org/10.1016/j.scitotenv.2009.07.006

Soorni J, Shobbar ZS, Kahrizi D, Zanetti F, Sadeghi K et al. (2022). Correlational analysis of agronomic and seed quality traits in Camelina sativa doubled haploid lines under rain-fed condition. Agronomy Journal 12 (2): 359. https://doi.org/10.3390/agronomy12020359

Sujith Kumar MS, Mawlong I, Singh D (2017). Phytosterol recovery from oilseeds: Recent advances. Journal of Food Process Engineering 40 (3): p.e12466. https://doi.org/10.1111/jfpe.12466

Suri K, Singh B, Kaur A, Yadav MP, Singh N (2020). Influence of microwave roasting on chemical composition, oxidative stability and fatty acid composition of flaxseed (Linum usitatissimum L.) oil. Food Chemistry 326: p.126974. https://doi.org/10.1016/j.foodchem.2020.126974

Teixeira da Silva JA, Dobránszki J (2016). Magnetic fields: how is plant growth and development impacted? Protoplasma 253 (2): 231-248. https://doi.org/10.1007/s00709-015-0820-7

Tkalec M, Malarić K, Pevalek-Kozlina B (2005). Influence of 400, 900, and 1900 MHz electromagnetic fields on Lemna minor growth and peroxidase activity. Bioelectromagnetics 26 (3): 185-193. https://doi.org/10.1002/bem.20104

Tripathi R, Agrawal SB (2016). Effect of supplemental UV-B on yield, seed quality, oil content and fatty acid composition of Brassica campestris L. under natural field conditions. Quality Assurance and Safety of Crops and Foods 8 (1): 11-20. https://doi.org/10.3920/QAS2013.0290

Upadhyaya C, Upadhyaya T, Patel I (2022). Attributes of non-ionizing radiation of 1800 MHz frequency on plant health and antioxidant content of Tomato (Solanum Lycopersicum) plants. Journal of Radiation Research and Applied Sciences 15 (1): 54-68. https://doi.org/10.1016/j.jrras.2022.02.001

Uquiche E, Jeréz M, Ortíz, J (2008). Effect of pretreatment with microwaves on mechanical extraction yield and quality of vegetable oil from Chilean hazelnuts (Gevuina avellana Mol). Innovative Food Science and Emerging Technologies 9 (4): 495-500. https://doi.org/10.1016/j.ifset.2008.05.004

Van Boxem K, Huntoon M, Van Zundert J, Patijn J, van Kleef M et al. (2014). Pulsed radiofrequency: a review of the basic science as applied to the pathophysiology of radicular pain: a call for clinical translation. Regional Anesthesia and Pain Medicine 39: 149-159. http://doi.org/10.1097/AAP.0000000000000063

Vian A, Davies E, Gendraud M, Bonnet P (2016). Plant Responses to High Frequency Electromagnetic Fields. Biomed Res. Int 1–1. https://doi.org/10.1155/2016/1830262.

Vollmann J, Eynck C (2015). Camelina as a sustainable oilseed crop: contributions ofplant breeding and genetic engineering. Biotechnology Journal 10: 525-535. https://doi.org/10.1002/biot.201400200

Watts JL (2016). Using Caenorhabditis elegans to uncover conserved functions of omega-3 and omega-6 fatty acids. Journal of Clinical Medicine 5 (2): 19. https://doi.org/10.3390/jcm5020019

Wroniak M, Rękas A, Siger A, Janowicz M (2016). Microwave pretreatment effects on the changes in seeds microstructure, chemical composition and oxidative stability of rapeseed oil. LWT- Journal of Food Science and Technology 68: 634-641. https://doi.org/10.1016/j.lwt.2016.01.013

Yang M, Huang F, Liu C, Zheng C, Zhou Q et al. (2013). Influence of microwave treatment of rapeseed on minor components content and oxidative stability of oil. Food Science Biotechnology 6: 3206-3216. https://doi.org/10.1007/s11947-012-0987-2

Ye M, Zhou H, Hao J, Chen T, He Z et al. (2021). Microwave pretreatment on microstructure, characteristic compounds and oxidative stability of Camellia seeds. Industrial Crops and Products 161: 113193. https://doi.org/10.1016/j.indcrop.2020.113193

Yeong SP, Law MC, You KY, Chan YS, Lee VC (2019). A coupled electromagnetic-thermal-fluid-kinetic model for microwave-assisted production of Palm Fatty Acid Distillate biodiesel. Applied Energy 237: 457-475. https://doi.org/10.1016/j.apenergy.2019.01.052

Ying Q, Wojciechowska P, Siger A, Kaczmarek A, Rudzińska M (2018). Phytochemical content, oxidative stability, and nutritional properties of unconventional cold-pressed edible oils. J. Food Nutr. Res 6 (7): 476-485. https://doi:10.12691/jfnr-6-7-9

Yoshida H, Hirakawa Y, Tomiyama Y, Nagamizua T, Mizushina Y (2005). Fatty acid distributions of triacylglycerols and phospholipids in peanut seeds (Arachis hypogaea L.) following microwave treatment. Journal of Food Composition and Analysis 18: 3-14. https://doi.org/10.1016/j.jfca.2003.12.004

Yoshida H, Tomiyama Y, Hirakawa Y, Mizushina Y (2006). Microwave roasting effects on the oxidative stability of oils and molecular species of triacylglycerols in the kernels of pumpkin (Cucurbita spp.) seeds. Journal of Food Composition and Analysis 19: 330-339. https://doi.org/10.1016/j.jfca.2004.10.004

Yu L, Zhou C, Fan J, Shanklin J, Xu C (2021). Mechanisms and functions of membrane lipid remodeling in plants. Plant Journal 107 (1): 37-53. https://doi.org/10.1111/tpj.15273

Zając M, Kiczorowska B, Samolińska W, Klebaniuk R (2020). Inclusion of camelina, flax, and sunflower seeds in the diets for broiler chickens: apparent digestibility of nutrients, growth performance, health status, and carcass and meat quality traits. Animals 10 (2): 321. https://doi.org/10.3390/ani10020321

Zaunschirm M, Pignitter M, Kienesberger J, Hernler N, Riegger C et al. (2018). Contribution of the ratio of tocopherol homologs to the oxidative stability of commercial vegetable oils. Molecules, 23 (1): 206. https://doi.org/10.3390/molecules23010206

Zhao S, Xiong S, Qiu C, Xu Y (2007). Effect of microwaves on rice quality. Journal of Stored Products Research 43 (4): 496-502. https://doi.org/10.1016/j.jspr.2007.02.002

Zubr J, Matthäus, B (2002). Effects of growth conditions on fatty acids and tocopherols in Camelina sativa oil. Industrial Crops and Products 15 (2): 155-162. https://doi.org/10.1016/S0926-6690(01)00106-6