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Influence of microwave roasting on chemical composition, oxidative stability and fatty acid composition of flaxseed (*Linum usitatissimum* L.) oil

Kanchan Suri[a], Balwinder Singh[b,*], Amritpal Kaur[a,*], Madhav P. Yadav[c,*], Narpinder Singh[a]

[a] Department of Food Science and Technology, Guru Nanak Dev University, Amritsar 143005, Punjab, India
[b] P.G. Department of Biotechnology, Khalsa College, Amritsar 143002, Punjab, India
[c] Eastern Regional Research Center, Agricultural Research Service, United States Department of Agriculture, 600 East Mermaid Lane, Wyndmoor, PA 19038, USA

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ABSTRACT

In this study, flaxseeds roasted at microwave (MW) powers of 180, 360 and 540 W for 5 and 10 min were evaluated for their influence on oil yield, chemical properties, carotenoid and chlorophyll contents, total phenolic content (TPC), radical scavenging activity (RSA), oxidative stability index (OSI), fatty acid composition and Maillard reaction products (MRPs). MW roasting at 540 W for 10 min significantly increased the oil yield, TPC, OSI, RSA, a* value, browning index, carotenoid and chlorophyll contents while decreased the L* and b* values of flaxseed oil (FSO). MRPs were detected only in oil of flaxseeds roasted at 540 W for 10 min. The level of stearic, palmitic, oleic, linoleic and α-linolenic acids were slightly changed and FTIR spectra showed minor variation in peak intensities of oils from different MW roasted flaxseeds. MW roasting (540 W for 10 min) is recommended for improving quality and stability characteristics of FSO.

1. Introduction

Flaxseed (*Linum usitatissimum* L., Family *Linaceae*), also known as linseed is a blue flowering annual herb grown as fiber or oil crop (Shim, Gui, Arnison, Wang, & Reaney, 2014). It is grown globally with a total estimated production of 2.65 million tonnes as reported in 2014 (Mandal & Kundu, 2019). The main flaxseed growing countries are Canada, India, China, USA and Ethiopia (Singh, Mridula, Rehal, & Barnwal, 2011), with Canada leading in its production and contributing around 33% (872.5 thousand tons) to the total worldwide production in the year 2014 (Mandal & Kundu, 2019). India accounted for about 10.2% of the total global flaxseed production (Singh et al., 2011).

Flaxseed contains oil (37.1%), carbohydrates (28.9%), protein (20.3%), dietary fiber (4.8%), moisture (6.5%) and minerals (2.4%) and is recognized as an important oilseed and fiber crop (Singh et al., 2011). Moreover, flaxseed is rich in phenolic compounds (lignans, ferulic and p-coumaric acid) and mucilage that are known for various bioactivities and beneficial intestinal function (Tuncel, Uygur, & Yüceer, 2017). Flaxseed oil (FSO) is well known for its exceptionally high content of α-linolenic acid (50–60%), tocopherols (20–70 mg/100 g) and carotenoids (~57 ppm), hence considered as an important ancient medicine and functional food ingredient (Goyal, Sharma, Upadhyay, Gill, & Sihag, 2014; Mohanan, Nickerson, & Ghosh, 2018). FSO has gained popularity as a functional ingredient in a variety of foods due to its chemical composition such as ω3 fatty acid (FAs) (rich in α-linolenic acid) and consumer awareness of its beneficial effects (Bekhit et al., 2018; Goyal et al., 2014). Consumption of FSO has several health benefits like lowering plasma low-density lipoproteins (LDL), reducing the risk of coronary heart diseases, inhibition of type-I and type-II diabetes and prevention of mammary and colon cancer (Kajla, Sharma, & Sood, 2015; Shim et al., 2014).

The quality of oils is strongly impacted by the way oilseeds are processed. The conventional processing pre-treatments of oilseeds include dehulling, cracking, milling, flaking, roasting, steaming and enzymatic hydrolysis (Dunford & Dunford, 2004). The objective of applying different pre-treatments in oilseeds is to obtain desirable quality changes in the extracted oils (Ghafoor, Özcan, Fahad, Babiker, & Fadimu, 2019). Among different pre-treatments, roasting has been widely investigated to improve oil recovery, coagulate proteins, inactivate enzymes, and to impart special flavor and aroma to oils (Suri, Singh, Kaur, & Singh, 2019; Suri, Singh, Kaur, Yadav, & Singh, 2019). Numerous studies have shown that roasting treatment of oilseeds

Abbreviations: FSO, Flaxseed oil; MW, Microwave; AV, Acid value; CD, Conjugated dienes; PV, Peroxide value; BI, Browning index; OSI, Oxidative stability index; MRPs, Maillard reaction products; FA, Fatty acid; RSA, Radical scavenging activity; HMF, 5-Hydroxymethylfurfural; SFA, Saturated FAs; MUFA, Monounsaturated FAs; PUFA, Polyunsaturated FAs; FTIR, Fourier Transform Infrared Spectroscopy

* Corresponding authors.
E-mail addresses: bbs171@rediffmail.com (B. Singh), amritft33@yahoo.co.in (A. Kaur), madhav.yadav@usda.gov (M.P. Yadav).

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influences phenolic and pigment contents, antioxidant activity, FAs and oxidative stability of oils (Ghafoor et al., 2019; Juhaimi, Özcan, Ghafoor, & Babiker, 2018; Suri, Singh, Kaur, & Singh, 2019; Suri, Singh, Kaur, Yadav et al., 2019). Efforts have been made to improve the yield and quality of FSO by pre-treatment of the flaxseed prior to screw pressing (Kajla et al., 2015). However, the novel and efficient process of pre-treating flaxseeds requires more detail investigation for the improvement of FSO yield, stability, nutritional value and physicochemical properties. Among different roasting methods, microwave (MW) roasting has earned a reputation of simple, fast, energy-efficient and impressive method for enhancing yield and quality of oil (Fathi-Achachlouei, Azadmard-Damirchi, Zahedi, & Shaddel, 2019). MW roasting reduces processing time since radiation energy is transported instantly and uniformly throughout the volume of food materials (Fathi-Achachlouei et al., 2019). Recent studies revealed that MW roasting can enhance the extraction efficiency of favourable oilseed components and nutraceuticals in the extracted oil (Fathi-Achachlouei et al., 2019; Ghafoor et al., 2019).

The intensity of any type of heat treatment induces varying degree of changes in the physicochemical composition of the food. MW roasting of flaxseed may influence the chemical composition, quality and stability characteristics of FSO and understanding the effect of MW process is of great importance. Although there are reports on chemical composition and health benefits of FSO, the impact of MW roasting of flaxseed on the oil quality and yield needs to be investigated. To optimize FSO yield and further enhance the oil quality in terms of its antioxidant potential, oxidative stability and nutraceutical properties, an appropriate time and MW power combination needs to be established. As such little information is available on the impact of MW roasting on chemical attributes, antioxidant potential and stability characteristics of FSO. Therefore, this study evaluated the effect of MW power (180, 360 and 540 W) and radiation time (5 and 10 min) on oil yields, chemical properties, pigment content, TPC, radical scavenging activity, Maillard reaction products, oxidative stability index and fatty acid composition of FSO.

2. Materials and methods

2.1. Materials

Flaxseeds were purchased from the retail market outlet in Amritsar, Punjab, India. The seeds were manually cleaned and stored at 4 °C in polypropylene bags for further use in treatment and analysis. All chemicals used were of analytical grade. FAME mixture (37 Component Mix) of Supelco (Bellefonte, PA, USA) and 5-hydroxymethylfurfural (HMF) were purchased from Sigma-Aldrich (St. Louis, USA).

2.2. Methods

2.2.1. Roasting and oil extraction

Flaxseeds (250 g) were roasted in three sets of experiments in a domestic microwave oven (LG Co. Ltd.) at a frequency of 2450 MHz and power of 180, 360 and 540 W (W) for a radiation time of 5 and 10 min. Flaxseeds were roasted in a glass petridish with 12 cm diameter. The selection of microwave (MW) power and radiation time was based on initial trials showing appropriate roasting with no burning of flaxseeds. It was observed that flaxseeds started burning and producing smoke by further increasing MW power to 720 W. After MW treatment, flaxseeds were allowed to cool at room temperature. The moisture content of unroasted flaxseeds was 4.70%. The flaxseeds roasted at MW powers of 180, 360 and 540 W for 5 min had moisture contents of 3.76, 3.43 and 2.98% respectively while those roasted for 10 min had a moisture content of 3.49, 3.16 and 1.97%, respectively. The flaxseed oil (FSO) from unroasted and MW roasted seeds were extracted using screw press oil expeller (M/s Rajkumar Agro Engineers Co., Nagpur, India) at a temperature below 60 °C. The oil obtained was then centrifuged at 10000 rpm for 5 min to settle down impurities, weighed to estimate the oil yield (%) and stored at −20 °C until further use.

2.2.2. Chemical properties

Acid value (AV) and peroxide value (PV) of oil were determined using the official method Ca 5a-40 and Cd 8b-90 of American Oil Chemists' Society (AOCS, 1997). Conjugated dienes (CD) were determined according to the IUPAC II D.23 method (IUPAC, 1987). The absorbance values were measured at 232 nm with Cary-60 Ultraviolet–Visible spectrophotometer (Agilent Technologies, USA).

2.2.3. Color

The color of oil was recorded with Hunter UltraScan VIS colorimeter (Hunter Associates, U.S.A.). The colour values were measured as L* (darkness (0) to lightness (1 0 0)), a* (greenness (−a*) to redness (+a*)) and b* (blueness (−b*) to yellowness (+b*)).

2.2.4. Pigments

The carotenoids and chlorophylls contents of oils were determined using procedure described in previous publication (Suri, Singh, Kaur, Yadav et al., 2019). 7.5 g of FSO was dissolved in cyclohexane and volume was made up to 25 ml. After proper mixing, the absorbance values for chlorophylls and carotenoids at 670 and 470 nm respectively were recorded using Cary 60 Ultraviolet–Visible spectrophotometer and results were calculated using the following equations.

$$\text{Chlorophylls}\,(\text{mg/kg}) = (\text{Abs}_{670} \times 10^6)/(613 \times 100 \times \text{density})$$

$$\text{Carotenoids}(\text{mg/kg}) = (\text{Abs}_{470} \times 10^6)/(2000 \times 100 \times \text{density})$$

2.2.5. Total phenolic content (TPC)

TPC of FSO was determined using the Folin-Ciocalteu (FC) reagent. Briefly, FSO (0.1 ml) was dissolved in 1 ml of *n*-hexane in an amber glass test tube followed by addition of 3 ml of sodium carbonate (10%). Then, 0.75 ml of previously diluted (10 fold) FC reagent was added and the mixture was kept at room temperature for 90 min. The absorbance of the mixture was measured at 710 nm using Cary 60 Ultraviolet–Visible spectrophotometer. TPC was expressed as mg gallic acid equivalents (GAE) per 100 g of FSO.

2.2.6. Radical scavenging activity (RSA)

The RSA of oil was determined using DPPH radical scavenging method as previously described (Suri, Singh, Kaur, & Singh, 2019). The absorbance of the control (DPPH solution) and oil reaction mixtures was measured at 515 nm with Cary 60 Ultraviolet–Visible spectrophotometer. The RSA was calculated using the following equation.

$$\text{RSA}(\%) = \left[1 - \frac{A_{30}}{A_c}\right] \times 100$$

where a_c is the absorbance of control DPPH solution and A_{30} is the absorbance of the oil reaction mixture after 30 min of incubation.

2.2.7. Maillard reaction products

2.2.7.1. Browning index (BI). The BI of oil was measured using the previously described method (Suri, Singh, Kaur, & Singh, 2019; Suri, Singh, Kaur, Yadav et al., 2019). The absorbance of the oil solution (1:20, oil and chloroform, w/v) was measured at 420 nm to determine non-enzymatic BI of oil samples.

2.2.7.2. 5-Hydroxymethylfurfural (HMF). HMF from FSO was extracted and quantified using the 1260 Agilent Infinity HPLC system (Agilent Technologies, USA) as described in our previous publications (Suri, Singh, Kaur, & Singh, 2019; Suri, Singh, Kaur, Yadav et al., 2019). In brief, 0.5 g FSO was vortex-mixed with 1 ml of methanol (70%) for 1 min, centrifuged for 5 min at 10,000 rpm and the upper layer was collected. The centrifugation step was repeated thrice and the combined

mixture of upper layers was diluted with methanol (70%) to 5 ml. The solution obtained was filtered through syringe filter (0.45 μm) for HPLC analysis. The peak detected at 285 nm was acquired for quantification of HMF in mg/kg.

2.2.8. Oxidative stability index (OSI)

OSI of oil was measured by the Professional Rancimat instrument (Model 892, Metrohm, Switzerland). FSO (3 g) was heated at 120 ± 1.6 °C and subjected to 20 l/h air inflow conditions. The OSI of oil was determined as an induction period and expressed in hours (h).

2.2.9. Fatty acid composition (FAC)

FAC was studied by derivatization of FAs to their methyl esters according to the Ce-1h-05 (American Oil Chemists' Society, 1997) method as described elsewhere (Suri, Singh, Kaur, Yadav et al., 2019). The contents of FAMEs were analyzed with 7820A Agilent gas chromatograph (Agilent Technologies, USA) hooked up with a flame-ionization detector (FID) and capillary column (DB-WAX, 30 m × 0.250 mm × 0.25 μm) according to the previously described method (Suri, Singh, Kaur, & Singh, 2019; Suri, Singh, Kaur, Yadav et al., 2019). FAMEs were identified and estimated by comparing with the standard. The relative percentage (g/100 g) of individual fatty acid (FA) was calculated by comparing retention time and peak area of unknown sample with FAME standard.

2.2.10. FTIR spectroscopy

FTIR spectra of oil were acquired (64 scans/sample) in the absorbance range of 500–3500 cm^{-1} with 4 cm^{-1} spectral resolution, on a Vertex-70spectrometer system (Brucker Optics, Germany) equipped with ATR assembly. The analysis was carried out at room temperature and spectra were corrected against the background spectrum of air. For each measurement, a drop of oil was placed onto the surface of the cleaned ATR crystal. Three spectra were collected for each oil sample, averaged and used for analysis.

2.3. Statistical analysis

All the analytical tests and experiments were carried out in triplicate and data reported as mean ± standard deviation (SD) values of these triplicates. Two-way analysis of variance (ANOVA) was performed to understand the influence of MW powers and radiation time on FSO quality and stability parameters. For statistical assessment, Pearson's correlation coefficient (r) and principal component analysis were employed on the data to establish relation between different parameters. The statistical software Minitab (Minitab Inc., State College, Pennsylvania, USA) was used for analysis.

3. Results and discussion

3.1. Oil yield

The yield of oil extracted from unroasted and MW roasted flaxseeds are given in Table 1. The yield of oil from the unroasted flaxseed was 26.0%, which is close to the previously reported yield of oil (27.4%) from flaxseeds using conventional solvent extraction method (Zanqui et al., 2015). The increase in MW power and radiation time had influenced the oil yield with the highest of 34.9% observed for flaxseed roasted at 360 W for 10 min. The MW treatment may cause modification in the cell wall, increases cell porosity and facilitates the passage of oil through cell walls (Fathi-Achachlouei et al., 2019). The obtained results were in agreement with the previously published results reporting an improvement in the yield of oil extracted from roasted milk thistle seeds (Fathi-Achachlouei et al., 2019) and rapeseed (Azadmard-Damirchi, Habibi, Hesari, Nemati, & Fathi, 2010). However, no significant increase in the oil yield with an increase in MW power and radiation time was observed. This might be due to loss of moisture from flaxseed at higher MW power and radiation time, thus making them more brittle and poorer in plasticity and elasticity. The brittleness may hinder the extraction of oil from flaxseeds. Wroniak, Rękas, Siger, and Janowicz (2016) also reported the adverse effect of prolonged microwave pre-treatment (800 W for 7 min) on oil extraction yield from rapeseeds. The F values showed a higher significant effect ($p \leq 0.005$) of radiation time than MW power on oil yield from flaxseeds (Table 2). A significant positive correlation between oil yield and MW roasting ($r = 0.798$, $p \leq 0.05$) was observed (Table 3).

3.2. Chemical properties

3.2.1. Acid value (AV)

AV act as an indicator of quality deterioration occurring in oil as it determines the amount of free FA produced as a result of triglyceride hydrolysis (Tenyang et al., 2017). The AV of FSO obtained from unroasted and MW roasted flaxseeds are given in Table 1. The unroasted FSO has AV of 0.73 mg KOH/g. The lower AV indicates that the oil contains less free FA. A recent study by Symoniuk, Ratusz, and Krygier (2017) has reported the AV in the range of 0.53 to 3.15 mg KOH/g in 15 cold-pressed FSO samples collected from local retail outlets in Poland. AV for MW roasted FSO varied from 0.78 to 1.18 mg KOH/g, with the highest for those roasted at 540 W for 10 min. MW roasting had slightly increased AV of FSO. The previously published study on flaxseed hull oil also reported an increase in AV from 1.5 to 2.9 mg KOH/g with heating at 110 °C for 12 h (Herchi et al., 2016). Similarly, other studies have also reported an increase in AV in poppy and chia seed oils by MW roasting (Ghafoor et al., 2019; Ozcan, Al-Juhaimi, Ahmed, Osman, & Gassem, 2019). An increase in AV of oil indicates a hydrolytic degradation of triglycerides and formation of free FA during roasting at high temperatures (Suri, Singh, Kaur, & Singh, 2019). However, an AV observed for unroasted and MW roasted FSO was lower than 4 mg KOH/g, the recommended limit of the international standards for oils used for human consumption (Suri, Singh, Kaur, Yadav et al., 2019). The F values showed a higher significant effect ($p \leq 0.005$) of radiation time than MW power on the AV of FSO (Table 2). The AV exhibited a highly significant positive correlation with MW roasting and SFA content ($r = 0.991$ and 0.962, respectively, $p \leq 0.005$) of FSO (Table 3).

3.2.2. Peroxide value (PV)

PV determines the stability of oil against oxidative degradation. It is widely used for the measurement of peroxides and hydro-peroxide forms due to oxidation in oils. The FSO obtained from unroasted flaxseeds had PV of 2.24 meq O_2/kg (Table 1). The previous study reported a significant difference in PV (varied from 1.23 to 4.50 meq O_2/kg) in 15 cold-pressed FSO samples purchased from the local Polish market (Symoniuk et al., 2017). The PV increased by roasting at MW power of 360 W for 5 min (5.63 meq O_2/kg) and then decreased at 540 W for 10 min (2.24 meqO_2/kg). The initial increase in PV of FSO observed at low MW power and radiation time might be due to the free radical attack on UFAs and formation of peroxides. However, due to their unstable nature, peroxides may get decomposed into secondary oxidation products (aldehydes, ketones, etc.) at high MW power and radiation time (540 W for 10 min). The results obtained concur with the previous studies reporting a similar trend in PV of hazelnut, soybean, olive and sunflower oil during MW heating at 600 W for 3, 6 and 9 min of heating time (Javidipour, Erinç, Baştürk, & Tekin, 2017). PV observed for unroasted and MW roasted FSO was lower than 10 meqO_2/kg, the recommended limit of the international standards for the oils in human nutrition (Kaur, Singh, Kaur, & Singh, 2020). The F values presented higher significant effect ($p \leq 0.005$) of radiation time than MW power on the PV of FSO (Table 2). The PV exhibited a highly significant positive correlation with CD ($r = 0.952$, $p \leq 0.005$) as shown in Table 3.

Table 1
Effect of MW roasting on oil yield, chemical properties, colour values, pigments, radical scavenging activity, total phenolic content, Maillard reaction products and oxidative stability index of flaxseed oils.

Parameters	Unroasted	180 W (5 min)	180 W (10 min)	360 W (5 min)	360 W (10 min)	540 W (5 min)	540 W (10 min)
Oil yield (%)	26.0 ± 0.09^{a}	30.1 ± 0.12^{b}	33.3 ± 0.12^{c}	33.6 ± 0.17^{c}	34.9 ± 0.16^{c}	33.9 ± 0.08^{c}	33.7 ± 0.12^{c}
AV (mg KOH/g)	0.73 ± 0.01^{a}	0.78 ± 0.01^{a}	0.88 ± 0.02^{b}	0.98 ± 0.01^{c}	1.02 ± 0.01^{d}	1.06 ± 0.01^{d}	1.18 ± 0.02^{e}
PV (meq O_2/Kg)	2.24 ± 0.16^{a}	3.22 ± 0.06^{b}	4.19 ± 0.14^{c}	5.63 ± 0.09^{e}	4.44 ± 0.08^{d}	3.22 ± 0.05^{b}	2.24 ± 0.06^{a}
CD (%)	1.63 ± 0.08^{b}	1.66 ± 0.07^{b}	1.80 ± 0.02^{c}	1.84 ± 0.07^{d}	1.78 ± 0.03^{c}	1.64 ± 0.01^{b}	1.61 ± 0.01^{a}
L*	69.15 ± 0.08^{e}	62.83 ± 0.07^{d}	58.52 ± 0.08^{c}	62.18 ± 0.06^{d}	51.18 ± 0.05^{b}	61.00 ± 0.06^{d}	27.09 ± 0.09^{a}
a*	14.88 ± 0.09^{a}	15.21 ± 0.06^{b}	15.89 ± 0.08^{b}	15.76 ± 0.08^{b}	17.34 ± 0.07^{d}	16.49 ± 0.09^{c}	22.44 ± 0.07^{e}
b*	117.49 ± 0.08^{d}	103.23 ± 0.10^{c}	96.52 ± 0.11^{c}	101.98 ± 0.08^{c}	85.16 ± 0.13^{b}	100.34 ± 0.11^{c}	46.26 ± 0.09^{a}
Chlorophylls (mg/kg)	1.45 ± 0.02^{a}	1.49 ± 0.02^{a}	1.54 ± 0.04^{a}	1.62 ± 0.05^{b}	1.69 ± 0.08^{c}	1.82 ± 0.06^{d}	2.08 ± 0.09^{e}
Carotenoids (mg/kg)	2.89 ± 0.02^{a}	3.11 ± 0.03^{b}	3.29 ± 0.06^{c}	3.32 ± 0.06^{d}	3.36 ± 0.05^{d}	3.42 ± 0.03^{d}	3.45 ± 0.05^{e}
TPC (mg GAE/100 g)	33.58 ± 1.32^{c}	27.14 ± 1.16^{b}	24.24 ± 1.01^{a}	45.16 ± 1.39^{e}	55.60 ± 0.89^{f}	42.32 ± 0.84^{d}	61.88 ± 1.72 ^{g}
RSA (% DPPH inhibition)	56.55 ± 0.25^{a}	57.05 ± 0.29^{a}	57.88 ± 0.80^{b}	58.21 ± 0.74^{c}	60.47 ± 0.55^{d}	59.31 ± 0.89^{c}	61.93 ± 0.67^{e}
BI ($Abs_{420\ nm}$)	0.195 ± 0.01^{a}	0.236 ± 0.03^{b}	0.244 ± 0.00^{b}	0.257 ± 0.01^{c}	0.315 ± 0.01^{de}	0.284 ± 0.00^{d}	0.336 ± 0.01^{e}
HMF (mg/kg)	nd	nd	nd	nd	nd	nd	2.89 ± 0.01^{a}
OSI (h)	0.52 ± 0.04^{b}	0.47 ± 0.02^{a}	0.59 ± 0.09^{b}	0.62 ± 0.07^{b}	0.81 ± 0.03^{c}	1.28 ± 0.04^{d}	2.38 ± 0.02^{e}

Values (mean ± SD, n = 3) with similar superscripts in a row do not differ significantly ($p \leq 0.05$) among MW roasting treatments. AV = Acid value; PV = Peroxide value; CD = Conjugated dienes; L* = darkness (0) to lightness (1 0 0); a* = redness (+a*) to greenness (−a*); b* = yellowness (+b*) to blueness (−b*); TPC = Total phenolic content; RSA = Radical scavenging activity; BI = Browning index; HMF = 5-Hydroxymethylfurfural; OSI = Oxidative stability index; nd = Not detected.

3.2.3. Conjugated dienes (CD)

CD represents the formation of primary oxidation products in oils (Suri, Singh, Kaur, & Singh, 2019; Suri, Singh, Kaur, Yadav et al., 2019). It is due to the shift in double bond position exhibited by methylene interrupted polyenes or dienes during oxidation (Hashemi et al., 2017). The level of CD in FSO obtained from unroasted and MW roasted flaxseeds is given in Table 1. The unroasted FSO had a CD content of 1.63%. These values concur with those reported for commercial cold-pressed FSO (Tańska, Roszkowska, Skrajda, & Dąbrowski, 2016). The MW roasting significantly influenced the level of CD (varied from 1.61 to 1.84%) in FSO. The level of CD in FSO was increased by increasing MW power from 180 to 360 W and decreased by further extension of MW power to 540 W for 10 min. The initial increase in CD content at low MW power (180 to 360 W) indicates the formation of primary oxidation products in oil. However, the decrease in CD values observed at high MW power and radiation time (540 W for 10 min) might be related to the accelerated degradation of hydroperoxides. Javidipour et al. (2017) reported similar trends in CD contents of hazelnut, olive, sunflower and soybean oils during MW heating at 600 W for 3, 6 and 9 min. They reported an increase in CD values by increasing MW heating from 3 to 6 min and decrease upon extending the heating time to 9 min. The F values showed a higher significant effect ($p \leq 0.05$) of MW power than radiation time on CD content of FSO as shown in Table 2.

3.3. Color

The color values of the unroasted and MW roasted FSO are given in Table 1. The L*, a* and b* value of oil from unroasted flaxseeds were 69.15, 14.88 and 117.49, respectively. Similar values of L* (60.05–63.71), a* (3.28–9.56) and b* (91.08–99.80) were reported by Choo, Birch, and Dufour (2007) for seven cold-pressed FSO sold in New Zealand. The unroasted FSO was brighter and lighter in color as indicated by its higher L* and b* values. The L* and b* values of FSO decreased while a* values increased gradually by increasing MW power and radiation time. The oil obtained from MW roasted seeds at 540 W for 10 min had L*, a* and b* values of 27.09, 22.44 and 46.26, respectively. The decrease in L* and b* values (darkness) and increase in a* value (redness) with MW roasting indicates darkening of FSO. A previous study by Tuncel et al. (2017) also reported a decrease in color values of oil obtained from infrared roasted flaxseeds. Similar changes in color values were reported for MW roasted pistachio (Ling, Yang, Li, & Wang, 2016) and rice bran (Thanonkaew, Wongyai, McClements, & Decker, 2012) oils. The oil color depends on the type and concentration of the pigments present in the oil (Suri, Singh, Kaur, Yadav et al., 2019). The enhanced release of pigments (chlorophyll and carotenoids) has been related to the changes in the color of roasted oils (Rabadán, Gallardo-Guerrero, Gandul-Rojas, Álvarez-Ortí, & Pardo, 2018; Suri, Singh, Kaur, Yadav et al., 2019). The changes in oil color also occurs due to the Maillard reaction and generation of some browning reaction by-products in oilseeds during roasting (Suri, Singh, Kaur, Yadav et al., 2019). The F values showed a higher significant effect ($p \leq 0.005$) of radiation time than the MW power on color values of FSO (Table 2). L* and b* exhibited a significant negative correlation ($r = -0.765$ and -0.784, respectively, $p \leq 0.05$), while a* exhibited a significant positive correlation with MW roasting ($r = 0.795$, $p \leq 0.05$) as shown in Table 3.

3.4. Chlorophyll and carotenoid contents

Chlorophyll and carotenoid contents of unroasted and MW roasted FSO are given in Table 1. The unroasted FSO had chlorophyll and carotenoid contents of 1.45 and 2.89 mg/kg respectively. Obranović et al. (2015) reported the difference in chlorophyll and carotenoid contents (varied from 0.23 to 0.86 and 1.02 to 2.78 mg/kg respectively) of oils obtained from four flaxseed varieties. The chlorophyll and carotenoid contents were gradually increased by increasing MW power and radiation time. The oils obtained from flaxseeds roasted at 540 W for 10 min showed higher chlorophyll and carotenoid contents (2.08 and 3.45 mg/kg respectively). The MW treatment of oilseeds causes thermal disintegration of a complex between proteins and pigments, resulting in the higher release of pigments in oils during extraction. Similar results of increment in the level of these pigments in oils with an increase in radiation time were reported in MW roasted rapeseeds (Rękas, Wroniak, & Ścibisz, 2017) and black cumin seeds (Mazaheri, Torbati, Azadmard-Damirchi, & Savage, 2019). The F values showed a higher significant effect ($p \leq 0.005$) of MW power on chlorophyll content and of radiation time on carotenoid content of FSO (Table 2). MW roasting showed a highly significant positive correlation with chlorophyll and carotenoid contents ($r = 0.946$, 0.923, respectively, $p \leq 0.005$) as shown in Table 3. The chlorophyll content exhibited a highly significant positive correlation with OSI ($r = 0.967$, $p \leq 0.005$) of FSO (Table 3). These pigments are known to provide an antioxidant activity, which plays a significant role in the stability of oils (Hashemi et al., 2017). Moreover, a significant negative correlation of chlorophyll content with L*, b* ($r = -0.873$, -0.878, respectively, $p \leq 0.05$) and significant positive correlation with a* value ($r = 0.921$, $p \leq 0.005$) was also observed.

Table 2
F values from ANOVA analysis of the data (MW power versus radiation time) of flaxseed oils shown in Table 1 and 4.

	DF	Oil yield	AV	PV	CD	L*	a*	b*	Chlorophylls	Carotenoids	TPC	RSA	BI	HMF	OSI	MUFA	PUFA	SFA
MW Power	2	12.71**	25.37**	31.59**	6.71*	56696.09**	2660.62**	2871.04**	56.27**	20.47**	562.20**	28.48**	29.11**	4563.0**	678.24**	489.26**	6863.16**	9807.11**
Radiation time	2	489.36**	60.10**	58.24**	5.52*	247074.42**	5271.64**	14246.60**	54.83**	218.73**	279.49**	80.01**	140.62**	4563.0**	426.69**	1037.09**	7881.12**	13197.96**
Interaction	4	6.61**	6.73**	17.71**	3.28*	48175.12**	1622.80**	2441.63**	15.68**	7.04**	202.16**	9.03**	10.46**	4563.0**	246.92**	122.74**	1865.10**	2602.07**

DF = degree of freedom; AV = Acid value; PV = Peroxide value; CD = Conjugated dienes, L* = darkness to lightness; a* = redness to greenness; b* = yellowness to blueness; TPC = Total phenolic content; RSA = Radical scavenging activity; BI = Browning index; OSI = Oxidative stability index; HMF = 5-Hydroxymethylfurfural; MUFA = Monounsaturated fatty acids; PUFA = Polyunsaturated fatty acids; SFA = Saturated fatty acids; *p ≤ 0.05, **p ≤ 0.005.

3.5. Total phenolic content (TPC)

The TPC of unroasted and MW roasted FSO is given in Table 1. The unroasted FSO showed TPC of 33.58 mg GAE/100 g oil. Our results contradict with previous study reporting higher phenolic content (76.8–307.3 ferulic acid equivalents/100 g) in seven cold-pressed FSO sold in New Zealand (Choo et al., 2007). The difference observed in TPC might be related to the difference in genotype, oil processing conditions and techniques used for estimation of phenolic compounds in FSO. There is a significant variation in TPC in the FSO obtained from flaxseeds roasted at different MW power and radiation time. The TPC decreased by roasting the flaxseeds at MW power of 180 W, while increased by increasing MW power from 360 to 540 W. The highest TPC (61.88 mg GAE/100 g) was observed in oil obtained from flaxseeds roasted at 540 W for 10 min. Our results concur with recent study describing the effect of MW roasting on phenolic content of black cumin seed oils (Mazaheri et al., 2019). The increased content of phenolics at high MW power and radiation time might be due to disruption of cell structure and release of bound phenolics in oils (Rękas et al., 2017). The F values showed higher significant ($p \leq 0.005$) effect of MW power than radiation time on TPC of FSO (Table 2). MW roasting exhibited a significant positive correlation with TPC ($r = 0.802$, $p \leq 0.05$). Furthermore, a significant positive correlation of TPC with RSA ($r = 0.887$, $p \leq 0.05$) was also observed (Table 3). This indicates that MW roasting increases phenolic content and antioxidant activity of FSO.

3.6. Radical scavenging activity (RSA)

The RSA of unroasted and MW roasted FSO is given in Table 1. The unroasted FSO has 56.55% RSA, which falls in the range of DPPH radical scavenging capacity (50.10–56.30%) reported for 15 cold-pressed FSO samples by Symoniuk et al. (2017). The MW power and radiation time showed a significant positive impact on the RSA of FSO. The RSA of MW roasted FSO ranged from 57.05 to 61.93% with the highest for those roasted at 540 W for 10 min. Similar results of an increase in RSA of apricot kernel oil by increasing MW power from 360 W to 540 W were reported in previous study (Juhaimi et al., 2018). The enhancement of RSA of MW roasted FSO might be attributed to the more release of pigments and phenolic compounds into the oil phase. The F values showed higher significant effect ($p \leq 0.005$) of radiation time than MW power on RSA of FSO (Table 2). A highly significant positive correlation of RSA with MW roasting, BI ($r = 0.933$ and 0.980, respectively, $p \leq 0.005$) and significant positive correlation with carotenoid content ($r = 0.821$, $p \leq 0.05$) was observed (Table 3). This correlation indicates that the increase in the RSA of FSO with MW roasting might be due to an increase in carotenoid content and the formation of browning compounds.

3.7. Maillard reaction products (MRPs)

Roasting facilitates the development of Maillard reaction and formation of browning products in oilseeds and it is important to analyze the presence of MRPs in oil obtained from roasted oilseeds (Suri, Singh, Kaur, & Singh, 2019; Suri, Singh, Kaur, Yadav et al., 2019; Zou, Gao, He, & Yang, 2018). The changes in the BI and HMF of MW roasted FSO were studied to determine the generation of MRPs and their passage in the oil phase (Suri, Singh, Kaur, & Singh, 2019; Suri, Singh, Kaur, Yadav et al., 2019). The BI and HMF content of the oil extracted from unroasted and roasted flaxseed is given in Table 1. The BI of FSO slightly increased with the increasing MW power and radiation time. The unroasted FSO has a BI of 0.195. The BI varied from 0.236 to 0.336 for MW roasted FSO with the highest for those roasted at 540 W for 10 min. The F values showed a higher significant effect ($p \leq 0.005$) of radiation time than MW power on BI of FSO (Table 2). A previous study by Raigar, Upadhyay, and Mishra (2017) also reported an increase in BI of peanut oil with increase in MW power and roasting time due to an

Table 3
Pearson correlation coefficients between the various properties of unroasted and MW roasted flaxseed oils.

	MW Roasting	AV	PV	L*	a*	b*	Chlorophylls	Carotenoids	TPC	RSA	HMF	OSI
Oil yield	0.798*											
AV	0.991**											
CD			0.952**									
L*	−0.765*											
a*	0.795*			−0.986**								
b*	−0.784*			0.998**	−0.979**							
Chlorophylls	0.946**			−0.873*	0.921**	−0.878*						
Carotenoids	0.923**											
TPC	0.802*				0.785*		0.812*			0.887*		
RSA	0.933**			−0.900*	0.902**	−0.905**	0.926**	0.821*				
BI	0.938**			−0.849*	0.833*	−0.866*	0.884*	0.878*		0.980**		
HMF		−0.993**		−0.921**	0.950**	−0.907**	0.821*					
OSI	0.834*						0.967**			0.852*	0.917**	
MUFA	−0.992**	−0.975**							−0.769*			−0.881*
PUFA	−0.965**	−0.948**							−0.864*			−0.777*
SFA	0.980**	0.962**							0.851*			0.808*

AV = Acid value; PV = Peroxide value; CD = Conjugated dienes; TPC = Total phenolic content; RSA = Radical scavenging activity; BI = Browning index; HMF = 5-Hydroxymethylfurfural; OSI = Oxidative stability index; MUFA = Monounsaturated fatty acids; PUFA = Polyunsaturated fatty acids; SFA = Saturated fatty acids; *$p \leq 0.05$; **$p \leq 0.005$.

increase in the rate of non-enzymatic browning reactions. The browning compounds might be responsible for the increased antioxidant activity as indicated by the highly significant positive correlation of BI with RSA and OSI ($r = 0.980$ and 0.760, respectively, $p \leq 0.005$) of FSO (Table 3).

The formation of HMF was estimated by HPLC analysis of oil extracted from unroasted and MW roasted flaxseeds. The HMF was not detected in oils obtained from unroasted flaxseeds and those roasted at MW powers of 180 (for 5 and 10 min), 360 (for 5 and 10 min) and 540 W (for 5 min). The HMF was detected at a level of 2.89 mg/kg in oil obtained from flaxseeds roasted at MW power of 540 W for 10 min. Recent studies has also reported the formation of HMF in oil obtained from the roasted black cumin seeds (Suri, Singh, Kaur, Yadav et al., 2019) and wheat germ (Zou et al., 2018). During the thermal processing of oilseeds, the interaction of reducing sugars with lipid oxidation products or amino acids results into generation of MRPs, which causes browning of oils (Suri, Singh, Kaur, & Singh, 2019; Suri, Singh, Kaur, Yadav et al., 2019; Zou et al., 2018). The F values showed a higher significant effect ($p \leq 0.005$) of MW power and radiation time on HMF of FSO (Table 2). HMF exhibited a highly significant positive correlation with OSI and a* ($r = 0.917$ and 0.950, $p \leq 0.005$), while a highly significant negative correlation with L* and b* ($r = -0.921$ and -0.907, respectively, $p \leq 0.005$) values (Table 3). The formation of HMF might be responsible for higher OSI of oil from flaxseeds roasted at 540 W for 10 min.

3.8. Oxidative stability index (OSI)

The OSI indicates the susceptibility of oil to oxidation, which depends mainly on the degree of unsaturation and the level of antioxidant compounds present in the oil (Suri, Singh, Kaur, & Singh, 2019). The OSI of unroasted and MW roasted FSO is given in Table 1. The unroasted FSO has an OSI value of 0.52 h. The FSO was characterized by low OSI due to its high α-linolenic acid content. A recent study by Mohanan et al. (2018) reported the OSI value of 2.4 h for commercial cold-pressed FSO. The MW roasting significantly increased the OSI of FSO. The OSI of MW roasted FSO varied from 0.47 to 2.38 h with the highest for those roasted at 540 W for 10 min (Table 1). Similar result of improvement in OSI was found in oils obtained from MW roasted rapeseeds (Rękas et al., 2017; Wroniak et al., 2016) and black seeds (Mazaheri et al., 2019). The improved OSI of MW roasted FSO could be attributed to the formation of MRPs during the roasting process, which positively influences the shelf life of oils (Suri, Singh, Kaur, Yadav et al., 2019). The F values showed higher significant effect ($p \leq 0.005$) of MW power than radiation time on OSI of FSO (Table 2). The OSI showed a significant positive correlation with MW roasting, RSA and SFA ($r = 0.834$, 0.852 and 0.808, respectively, $p \leq 0.05$), while the significant negative correlation with MUFA and PUFA (($r = -0.881$ and $r = -0.777$, respectively, $p \leq 0.05$) of FSO as shown in Table 3. A previous study also reported a negative correlation of UFA with OSI of oil extracted from roasted black cumin seeds (Suri, Singh, Kaur, Yadav et al., 2019).

3.9. Fatty acid composition (FAC)

The FAC of unroasted and MW roasted FSO is given in Table 4. The five FAs detected in FSO were α-linolenic (C18:3n3c), oleic (C18:1n9c), linoleic (C18:2n6c), palmitic (C16:0) and stearic (C18:0) acid. The level of saturated (SFA), monounsaturated (MUFA) and polyunsaturated (PUFA) FAs in unroasted FSO were 10.88, 20.85 and 68.27%

Table 4
Effect of MW roasting on the fatty acid composition of flaxseed oils.

Fatty acids	Unroasted	180 W (5 min)	180 W (10 min)	360 W (5 min)	360 W (10 min)	540 W (5 min)	540 W (10 min)
C16:0 (Palmitic)	5.63 ± 0.01 ^{a}	5.69 ± 0.01^{b}	5.75 ± 0.01^{b}	5.83 ± 0.01^{c}	5.95 ± 0.01^{d}	6.01 ± 0.01^{e}	6.08 ± 0.02^{e}
C18:0 (Stearic)	5.25 ± 0.01^{a}	5.28 ± 0.01^{ab}	5.30 ± 0.01^{b}	5.59 ± 0.01^{c}	5.80 ± 0.01^{d}	5.95 ± 0.01^{e}	5.98 ± 0.01^{e}
C18:1n9c (Oleic)	20.85 ± 0.01^{e}	20.80 ± 0.02^{d}	20.75 ± 0.01^{c}	20.73 ± 0.01^{c}	20.67 ± 0.01^{b}	20.60 ± 0.01^{a}	20.54 ± 0.01^{a}
C18:2n6c (Linoleic)	13.94 ± 0.02^{e}	13.93 ± 0.01^{e}	13.92 ± 0.02^{d}	13.89 ± 0.01 ^{cd}	13.81 ± 0.01^{b}	13.79 ± 0.01^{a}	13.79 ± 0.01^{a}
C18:3n3c (α-Linolenic)	54.33 ± 0.01^{d}	54.30 ± 0.01^{e}	54.28 ± 0.01^{e}	53.96 ± 0.01^{d}	53.77 ± 0.02^{c}	53.65 ± 0.01^{b}	53.61 ± 0.01^{a}
MUFA	20.85 ± 0.01^{e}	20.80 ± 0.02^{d}	20.75 ± 0.01^{c}	20.73 ± 0.01^{c}	20.67 ± 0.01^{b}	20.60 ± 0.01^{a}	20.54 ± 0.01^{a}
PUFA	68.27 ± 0.01^{d}	68.23 ± 0.02^{d}	68.20 ± 0.01^{d}	67.85 ± 0.01^{c}	67.58 ± 0.01^{b}	67.44 ± 0.02^{a}	67.40 ± 0.01^{a}
SFA	10.88 ± 0.01^{a}	10.97 ± 0.01^{b}	11.05 ± 0.01^{c}	11.41 ± 0.01^{d}	11.75 ± 0.01^{d}	11.96 ± 0.00^{e}	12.07 ± 0.01^{f}

Values (mean ± SD, n = 3) with similar superscripts in a row do not differ significantly ($p \leq 0.05$) among MW roasting treatments. MUFA = Monounsaturated fatty Acids, PUFA = Polyunsaturated fatty Acids, SFA = Saturated fatty acids.

respectively. A similar proportion of SFA (11.96%), MUFA (21.48%) and PUFA (66.55%) was reported by Tuncel et al. (2017) in FSO. A high proportion of PUFA (α -linolenic and linoleic acid), followed by MUFA (oleic acid) and a low proportion of SFA (palmitic and stearic acid) were found in FSO. The predominant FA in FSO was α-linolenic acid, which constitutes about 54.33% of the total lipid content. A recent study by Symoniuk et al. (2017) reportedα-linolenic acid content in the range of 44.90–64.62% for fifteen FSO samples collected from Poland. The MUFA, PUFA and SFA content of FSO varied slightly depending upon the MW power and radiation time (Table 4). The proportion of SFA was slightly increased (12.07%) while the level of MUFA (20.54%) and PUFA (67.40%) were slightly decreased in FSO obtained from seeds roasted at 540 W for 10 min (Table 4). The slight changes in FAC of FSO might be due to the degradation of UFA during roasting at higher MW power and radiation time. Similar results were reported in previous studies for oils obtained from MW roasted Perah seed (Li, Ali, Muhammad, Othman, & Noor, 2018) and milk thistle seed oils (Fathi-Achachlouei et al., 2019). The F values revealed a higher significant effect ($p \leq 0.005$) of radiation time than MW power on MUFA, PUFA and SFA contents of FSO (Table 2). MW roasting exhibited a highly significant positive correlation with SFA ($r = 0.980$, $p \leq 0.005$) and negative correlation with MUFA and PUFA ($r = -0.992, -0.965$, respectively, $p \leq 0.005$) contents as shown in Table 3.

3.10. FTIR spectroscopy

FTIR is a quick method for assessing the thermal-oxidative changes in the oils. The FTIR spectra of FSO was acquired in the region of 3500–500 cm^{-1}. Most of the spectral information was observed from 3100 to 2800 cm^{-1} and 1800 to 700 cm^{-1} regions. Fig. 1(A) shows a representative FTIR spectra of FSO with visible peaks at 3008, 2929, 2854, 1745, 1651, 1465, 1371, 1237, 1161, 1095 and 725 cm^{-1}. A previous study by Chauhan, Chester, Khan, Tamboli, and Ahmad (2015) also noted similar peaks in the FTIR spectra of FSO extracted using different extraction methods. The peak observed at 3008 cm^{-1} (ascribed to CH stretching symmetric vibration of the *cis*-olefinic groups, =CH), 2929 and 2854 cm^{-1} (attributed to asymmetric and symmetric stretching vibrations of CH bonds of CH_2 aliphatic groups, respectively), 1745 cm^{-1} (correspond to carbonyl (C=O) group stretching vibrations), 1651 cm^{-1} (assigned to the stretching vibration of disubstituted cis C=C of the unsaturated acyl groups), 1465 cm^{-1} (designated to bending vibrations of CH bonds of aliphatic CH_2 and CH_3 groups), 1371 cm^{-1} (assigned to bending symmetric vibrations of CH bonds of CH_2 groups), 1237, 1161 and 1095 cm^{-1} (associated with the stretching vibration of C−O group in esters and bending vibration of CH bonds of aliphatic CH_2 groups) and 725 cm^{-1} (attributed to overlap of the CH_2 rocking vibrations and out-of-plane vibration of cis-disubstituted olefins) were designated according to previous FTIR studies of oils (Gutiérrez, Quiñones-Segura, Sanchez-Reinoso, Díaz, & Abril, 2017; Kaur, Singh, Kaur, & Singh, 2019; Ozulku, Yildirim, Toker, Karasu, & Durak, 2017).

Fig. 1(B) shows the FTIR spectra of FSO obtained from unroasted flaxseeds and those roasted at different MW power and radiation time. FTIR spectra do not show any marked difference in oils of unroasted and MW roasted flaxseeds. The overall signal pattern of oils from unroasted and MW roasted flaxseeds looked similar to each other. However, upon close examination, a slight variation in peak intensities at certain wavenumbers was observed in oils of MW roasted flaxseeds. The oil obtained from flaxseeds roasted at MW power of 540 W for 10 min showed a slight decline in peak intensity at 3008 cm^{-1} and a slight increase in peak intensities at 2929 and 2854 cm^{-1} in comparison to unroasted FSO. This might be due to the disappearance of cis-olefinic C−H double bonds in UFA of FSO at high MW power and radiation time. A slight increase in peak intensities observed at 2929 and 2854 cm^{-1} indicate some chemical changes in MW roasted FSO due to advanced state of oxidation. The peak observed at 3008 cm^{-1} is linked with the level of UFA while peaks observed at 2929 and 2854 cm^{-1} are linked with the level of SFA in oils as stated in previous studies (Kaur et al., 2019; Ozulku et al., 2017). With an increase in MW power and radiation time, a slight increase in the level of SFA (stearic and palmitic acid) and decrease in UFA content (oleic, linoleic and α-linolenic acid) were observed in FSO (Table 4). Previous studies had also correlated the degree of unsaturation and saturation with peak intensities at 3008, 2929 and 2854 cm^{-1} of edible oils (Kaur et al., 2019; Ozulku et al., 2017; Suri, Singh, Kaur, & Singh, 2019; Suri, Singh, Kaur, Yadav et al., 2019). A slight increase in intensities of peaks at 1745 and 1161 cm^{-1} with an increase in MW power and radiation time were observed in FSO. This might be due to minor changes in CD content of FSO with an increase in MW power and radiation time. A similar increase in peak intensity near 1161 cm^{-1} with MW roasting was observed in walnut (Liang et al., 2013) and groundnut (Ali, Islam, Othman, & Noor, 2017) oils. The changes in peaks intensities at 1161 and 1745 cm^{-1} corresponds to hydrolysis of carbonyl ester functional groups into ketones and formation of secondary oxidation products from peroxides and

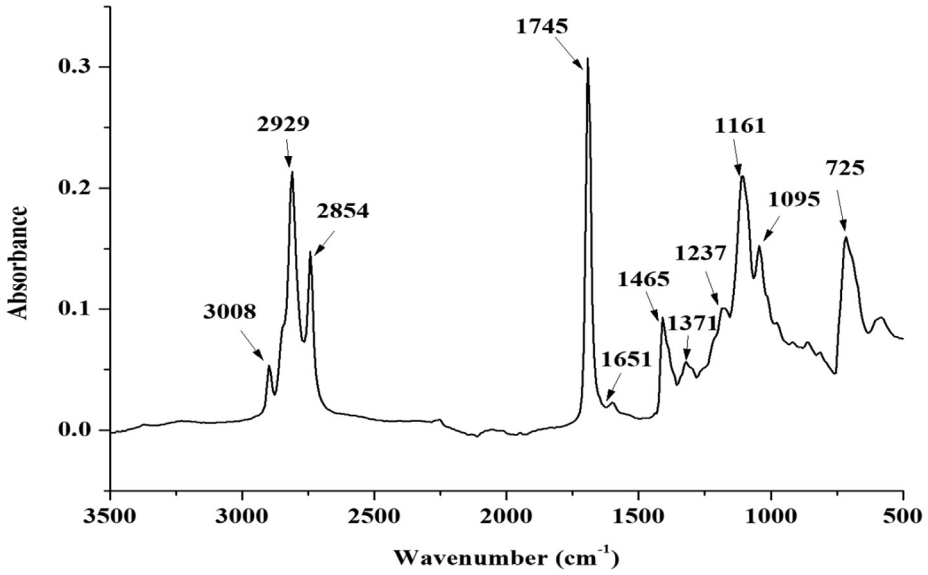

Fig 1A. FTIR spectrum of flaxseed oil at room temperature (25 °C).

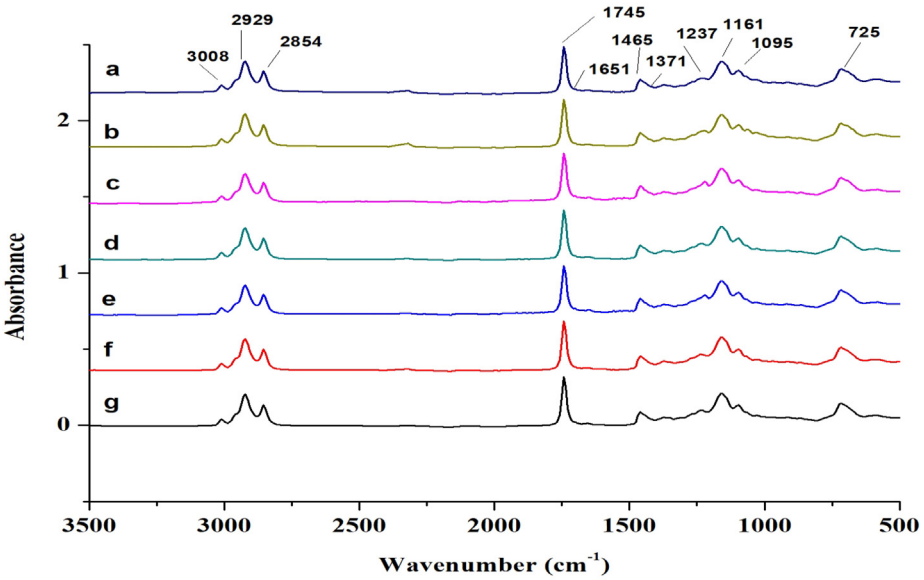

Fig. 1B. FTIR spectra of unroasted and MW roasted (a: unroasted; b: 180 W for 5 min; c: 180 W for 10 min; d: 360 W for 5 min; e: 360 W for 10 min; f: 540 W for 5 min; g: 540 W for 10 min) flaxseed oils.

hydroperoxides (Srivastava & Semwal, 2015). No major change in the intensities of peaks at 1651, 1465, 1371, 1237, 1095 and 725 cm^{-1} wavenumbers were observed in MW roasted FSO in comparison to unroasted FSO. Mulla, Ahmed, and Al-Sharrah (2018) also observed no significant changes in the peaks corresponding to these wavenumbers in the oven and MW roasted garden cress seed oils.

4. Principal component analysis

In order to correlate the results of chemical properties, FAC, chlorophyll and carotenoid contents, oxidative stability, TPC, RSA and MRPs of unroasted and MW roasted FSO, the multivariate analysis was performed. Principal components analysis (PCA) was carried out to know the impact of MW roasting on these parameters and results were graphically presented using loading and score plots (Fig. 2A & B). The eigenvalues higher than one were considered to determine the relative contributions of principal components (PC) in the overall total data variability. The first and second PC (PC1 and PC2) explained 90.7% variability within the observations. The contributions of PC1 and PC2 in the overall total data variability are shown in Table S1. The PC1 and PC2 accounted for 74.5 and 16.2% variability, respectively. The parameters that contributed to construction of PC1 were chlorophyll content (0.285), RSA (0.283), AV (0.276), BI (0.274), SFA (0.268), a* (0.273), OSI (0.271), MUFA (−0.278), b*(−0.267), L*(−0.266) and PUFA (−0.262). While, PV (0.595), CD (0.511), carotenoids (0.309) and HMF (−0.276) mainly contributed to building up PC2.

Fig. 2A shows the score plot between PC1 and PC2, where oil samples that showed typical similar characteristics were placed together. As evident from the score plot, FSO placed in quadrant I (unroasted and MW roasted at 180 W for 5 min) and II (MW roasted at 180 W for 10 min and 360 W for 5 min) had higher colour (L* and b*) values, MUFA and PUFA contents in comparison to those placed in quadrant III (MW roasted at 360 W for 10 min and 540 W for 5 min) and IV (MW roasted at 540 W for 10 min). The oils placed in Quadrant I had low OSI, high color values, MUFA and PUFA contents. The oil obtained from flaxseeds roasted at 540 W for 10 min (placed in Quadrant IV) showed the most distinctive behaviour among all oils. It had the highest OSI which could be attributed to the formation of MRPs, in addition, to increase in chlorophyll and carotenoid contents upon roasting. From the loading plot (Fig. 2B), it is evident that OSI

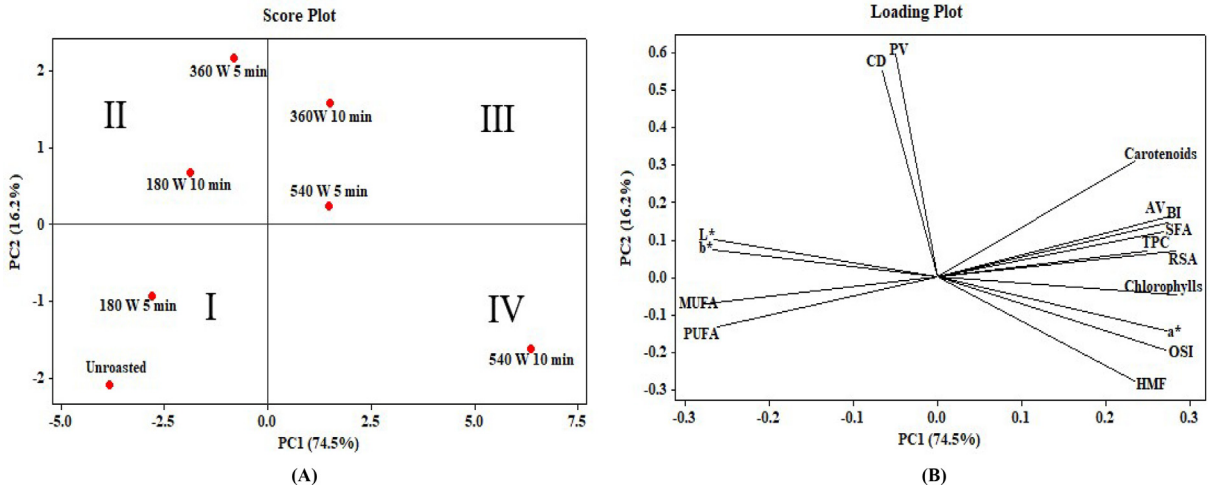

Fig. 2. Principal component analysis score plot (A) and loading plot (B) describing the relationship among different parameters of unroasted and MW roasted flaxseed oils at 180, 360 and 540 W for 5 and10 min.

showed close relation with chlorophyll content and HMF, indicating the major contribution of pigments and MRPs in increasing oxidative stability of MW roasted FSO. Moreover, TPC, RSA, SFA, BI and carotenoid content were positively correlated with OSI while MUFA, PUFA and color values exhibited negative correlation. Thus, FSO having higher chlorophyll and carotenoid contents, MRPs, TPC, RSA and SFA while lower PV, CD and PUFA contents after MW roasting had higher oxidative stability.

5. Conclusion

This study investigated the effect of different MW power and radiation time on the chemical properties and quality characteristics of FSO. The oil yield, TPC, RSA, BI, OSI, a* value, chlorophyll and carotenoid contents of FSO were increased while L* and b* values declined significantly with an increase in MW power and radiation time. The MW roasting at 540 W for 10 min resulted in the formation of MRPs and greater leaching of phenolic compounds, and pigments into the oil. The decrease in color values (L* and b* values) and increase in OSI of FSO relates with the rise in BI, pigments and formation of MRPs. The FTIR spectra of FSO showed minor changes in peak intensities which relate with changes in the level of SFA and UFA with increment in MW power and radiation time. FSO is considered as a healthy oil due to the presence of UFA (oleic, linoleic and α-linolenic acid) composition. Owing to higher oil yield and improved quality characteristics, MW pretreatment at 540 W for 10 min is recommended for extracting oil from flaxseeds for various applications in the food and pharmaceutical industries.

CRediT authorship contribution statement

Kanchan Suri: Investigation, Data curation, Writing - original draft. **Balwinder Singh:** Conceptualization, Data curation, Formal analysis, Resources, Software, Writing - review & editing. **Amritpal Kaur:** Conceptualization, Methodology, Funding acquisition, Project administration, Resources, Formal analysis. **Madhav P. Yadav:** Conceptualization, Resources, Supervision, Validation. **Narpinder Singh:** Resources, Data curation, Validation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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