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Effect of Microwave Roasting on Chemical Composition, Oxidative Stability, and Sensory Properties of Golden and Brown Flaxseed Oils: A Comparative Study

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HIGHLIGHTS:

- Microwave roasting modified the composition and oxidative stability of flaxseed oil.
- Short roasting (3 min) maintained antioxidants and improved sensory quality.
- Prolonged roasting increased oxidation and reduced polyunsaturated fatty acids levels.
- Optimal roasting balanced flavor quality and nutritional value.
- Findings support the industrial application of mild microwave roasting for flaxseed oil.

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Abbreviations
AnV=Anisidine Value
AOAC=Association of Official Analytical Chemists
AV=Acid Value
FA=Fatty Acid
FFA=Free Fatty Acid
FSO=Flaxseed Oil
GAE=Gallic Acid Equivalents
ISO=Organization for Standardization
IV=Iodine Value
MDA=Malondialdehyde
PUFA=Polyunsaturated Fatty Acid
PV=Peroxide Value
TC=Tocopherol Content
TPC=Total Phenolic Content

ABSTRACT

Background: Flaxseed (*Linum usitatissimum L.*) Oil (FSO) is valued for its high content of Polyunsaturated Fatty Acids (PUFAs) and natural antioxidants but is susceptible to oxidative degradation during processing. The objective of this study was to evaluate the effects of microwave heat treatment on the compositional characteristics, oxidation stability, and sensory quality of Golden and Brown FSOs.

Methods: Two flaxseed varieties were roasted at 2450 MHz for 3, 6, 9, and 12 min. The proximate composition (moisture, ash, fiber, protein, and oil), fatty acid profile, Tocopherol (TC) and Total Phenolic Contents (TPC), and oxidative stability parameters (Peroxide Value [PV], Acid Value [AV], Anisidine Value [AnV], Iodine Value [IV], and Malondialdehyde [MDA]) were determined using standard Association of Official Analytical Chemists (AOAC) and Organization for Standardization (ISO) methods. Sensory attributes (color, transparency, odor, flavor, and overall acceptability) were evaluated by a trained panel using a 5-point hedonic scale.

Results: Microwave roasting affected FSO composition and quality in a time-dependent manner. Fiber, ash, and protein did not change significantly, whereas moisture decreased from 6.24% to 3.51% (Golden) and 6.02% to 3.03% (Brown), and FSO content increased from 32.54% to 35.38% and 33.43% to 36.60%, respectively. Saturated Fatty Acids (SFA) were increased and Polyunsaturated Fatty Acids (PUFA) decreased with prolonged roasting, suggesting partial oxidation of Unsaturated Fatty Acids (USFA). Tocopherol (TC) and Total Phenolic Contents (TPC) were decreased, while oxidative parameters ((Peroxide Value [PV], Acid Value [AV], Anisidine Value [AnV], and Malondialdehyde [MDA])) increased and Iodine Value (IV) decreased over time. Sensory evaluation was highest at 3 min, suggesting short-term roasting optimally balances oil yield, nutritional quality, and sensory attributes.

Conclusion: Optimized control of microwave roasting can optimize FSO production, balancing nutritional quality, sensory properties, and industrial applicability.

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Introduction

Microwave ovens have been widely used in food science worldwide, and the use of microwaves for cooking or reheating is commonly used in households (Anjum *et al.*, 2006). Although using a microwave oven can provide several advantages and benefits, its adverse effects on the composition and nutritional quality of food remain a controversial issue (Mohammed *et al.*, 2016). Regarding lipid food sources, microwave heating has been studied to assess its effects on different animal and vegetable oils, as well as the thermo-oxidative stability of common oils and fats (Hashemi *et al.*, 2017). Many previous studies have demonstrated how microwave application in home settings affects different quality properties of seed oil (Seedea, 2025; Suri *et al.*, 2020; Zou *et al.*, 2018). However, the influence of microwave heating on a wide range of seed oils has not yet been clearly characterized, and further investigation in this field is required.

Flaxseed Oil (FSO) is obtained from *Linum usitatissimum* L., which is recognized as an important oilseed species worldwide. In 2024, global flaxseed production was approximately 2.7 million metric tons, with Russia leading the world in output (~1.36 million tons), followed by Kazakhstan and Canada. Global flaxseed imports in that year reached ~693,000 tons, with Russia responsible for about 76% of that volume (Seedea, 2025)

The color of flaxseeds ranges from deep brown to light yellow (Morris, 2007). These seeds are rich in α-linolenic acid and provide a high intake of dietary fiber. Health benefits of flaxseeds include the reduction of cardiovascular and cancer risks, along with the suppression of inflammatory processes linked to impaired blood circulation and arterial plaque development (Ghosh *et al.*, 2014; Singh *et al.*, 2011). Due to their health benefits, flaxseeds are widely used in various varieties, including whole seeds, oil, flour, supplements, and basic food products (Campos, 2019). However, its high Polyunsaturated Fatty Acid (PUFA) content makes flaxseed highly susceptible to oxidation during frying and roasting. Additionally, studies had reported that microwave heating may lead to harmful compound formation in flaxseed. Although some research has investigated the impact of microwaves on flaxseed, further investigation is still needed to clarify its overall influence (Suri, 2020). Previous studies have not comprehensively described the influence of microwave treatment on flaxseeds, including changes in lipid fractions over extended roasting times and the alteration of remaining constituents.

Unlike previous studies, this study uniquely compares two flaxseed varieties (Golden and Brown) under identical microwave conditions, evaluating their chemical composition, oxidative stability, and sensory quality. Sensory quality is highlighted as a decisive factor influencing consumers' initial purchasing decisions, representing a novel and practical aspect of this study. Therefore, this study investigates the effects of microwave roasting on the composition and oxidative stability of oils from two flaxseed varieties, and evaluates the sensory differences between roasted and unroasted seeds.

Materials and methods

Seed samples

Brown and Golden flaxseeds were purchased in Nanjing City, China. The seed samples were manually selected to eliminate damaged seeds, then selected for uniformity based on seed weight, ranging from 3.2 to 3.8 mg for both varieties. The samples were separated into around 20 parts, packed in polyethylene vacuum bags, and maintained at 4 ºC until analysis.

Microwave roasting of flaxseed

Flaxseeds were placed in Pyrex Petri dishes (Pyrex®, Corning, USA) with a diameter of 12.0 cm, forming a uniform layer approximately 2–3 mm thick. The dishes were then covered, and the flaxseeds were roasted in a Panasonic NN-SM332 consumer-model microwave oven (Panasonic, Japan) at a frequency of 2450 MHz for 3, 6, 9, and 12 min separately. For extract the oil, the roasted seeds were first cooled to room temperature, homogenized, and then crushed.

Moisture content

Before roasting, the water content of whole flaxseeds was measured following Association of Official Analytical Chemists 925.10 (AOAC, 2019). Flaxseed samples were dried at 105 ºC (DHG-9145, Shanghai Yiheng Instruments Co., China) until constant weight was attained to determine their water content. The moisture content (%) was calculated according to the following equation:

$$\text{Moisture content (\%)} = \frac{W_1 - W_2}{W_1} \times 100$$

Where W_1 and W_2 correspond to the initial and final weights of the sample, respectively.

Oil extraction

Total oil from flaxseeds was extracted using an SZF-06C Fat Analyzer Soxhlet Extraction Apparatus (Shanghai Zhicheng Analytical Instrument Manufacturing Co., China) for 5 h with petroleum ether (reagent grade ≥99%, 40-60 ºC boiling range, M011–500G, Merck, Germany) as the solvent. The extracted oil was concentrated under reduced pressure at ≤40 ºC, and subsequently dried with anhydrous sodium sulfate (S5881, Sigma-Aldrich, USA) to remove residual moisture and impurities. The purified oil samples

were stored in amber vials at -18 ºC until analysis to prevent oxidation.

Analysis of FSO residues

The contents of crude protein (AOAC 2006.03), fat (AOAC 920.39), fiber (AOAC 962.09), and ash (AOAC 923.03) were determined using AOAC official methods (AOAC, 2019). Total carbohydrate content (%) was determined as follows: Total carbohydrate (%) = 100−(% Moisture content + % Crude protein + % Crude fat + % Crude fiber + % Total ash).

-Crude protein

About 1.0 g of finely ground sample was treated with concentrated sulfuric acid (H_2SO_4, Sigma-Aldrich, USA) in the presence of a $CuSO_4$-K_2SO_4 catalyst mixture until complete digestion yielded a clear solution. The digest was subsequently neutralized and distilled with 40% sodium hydroxide solution (NaOH, Merck, Germany) using a Kjeldahl apparatus (Foss, Denmark). The liberated ammonia was absorbed in 4% boric acid solution and titrated with 0.1 N hydrochloric acid (HCl, Merck, Germany). Total nitrogen was determined using AOAC Official Method 2006.03 (AOAC, 2019), and curde protein levels were calculated by multiplying the nitrogen value by 6.25. The nitrogen content (%N) was calculated using the following equation:

$$\%N = \frac{(V_1 - V_0) \times N \times 14.007}{m} \times 100$$

Where V_1 and V_o are the HCl volumes for sample and blank titrations, N is the HCl concentration, m is the sample mass, and 14.007 is the atomic weight of nitrogen (g/mol).

The crude protein content (%) was then calculated as:

$$\%Protein = \%N \times 6.25$$

-Crude fiber

Approximately 2.0 g of the defatted sample was consecutively boiled for 30 min each in 1.25% sulfuric acid (H_2SO_4) and 1.25% NaOH solutions, with thorough washing between treatments. The residue obtained was thoroughly rinsed in succession with hot distilled water, 1% HCl, and ethanol, followed by drying at 105 ºC to constant mass. The dried material was subsequently incinerated in a muffle furnace (SX2-5-12, China) at 550 ºC for 3 h. The crude fiber content was determined from the weight loss after ashing, following the AOAC Official Method 962.09 (AOAC, 2019).

-Ash content

About 2.0 g of dried sample was transferred into a pre-heated porcelain crucible and ashed in a muffle furnace (SX2-5-12, China) at 550 ºC for 4 h until a white ash or light gray residue was obtained. After ashing, the crucible was cooled in a desiccator to room temperature and weighed to determine the remaining residue. Ash content (%) was determined from the weight of the inorganic residue using AOAC Official Method 923.03 (AOAC, 2019).

Ash content (%) was calculated using the formula below:

$$\%Ash = \frac{(W_2 - W_0)}{(W_1 - W_0)} \times 100$$

Where W_o is the empty crucible, W_1 holds the sample before ashing, and W_2 contains the ash after incineration.

Total Tocopherol (TC) and Phenolic Content (TPC) of FSO

-TC

TC in flaxseed were determined using the colorimetric approach reported by Arias-Santé *et al.* (2024). About 200 mg of oil was dissolved in 5 ml of toluene (Merck, Germany), then 3.5 ml of 2,2-bipyridine solution (0.07% w/v) was combined with 0.5 ml of $FeCl_3 \cdot 6H_2O$ solution (0.2% w/v; Sigma-Aldrich, USA), and the mixture was shaken thoroughly. The mixture was then made up to 10 ml with 95% ethanol (Merck, Germany). Following a 1-min incubation, the solution's absorbance was measured at 520 nm with a UV-1800 spectrophotometer (Shimadzu, Japan). A calibration curve was prepared using α-tocopherol standard solutions in the range of 0.5 - 5.0 µg/ml. Tocopherols in the extracts were determined using α-tocopherol as a standard and expressed as mg α-tocopherol equivalents per kg of oil. The content was calculated using the following formula:

$$\text{Total tocopherol } \left(\frac{\text{mg}}{\text{kg}}\right) = \frac{\text{C x V}}{\text{m}}$$

Where C is the α-tocopherol concentration obtained from the calibration curve (mg/ml), V the reaction mixture volume (ml), and m the mass of the oil sample (kg).

-TPC

Total phenols were determined by the Folin-Ciocalteu method with minor modifications, following Sumara *et al.* (2023). FSO was mixed with 20 ml of ethanol-water (70:30, Merck, Germany) and sonicated for 30 min at room temperature. After centrifugation at 5000 revolutions per minute (rpm) for 10 min (H1650, Xiangyi, China), the supernatant was used for TPC determination. Supernatants of the sample extracts were combined with 2.5 ml of Folin-Ciocalteu solution (Sigma-Aldrich, USA) and incubated at 25 ºC for 8 min. After standing at room temperature for 10 min, 1.5 ml of 20% (w/v) sodium carbonate solution (Na_3CO_3, Merck, Germany) was added to the mixture. Then, it was heated in a water bath (HH-S6, Jiangsu Jintan Medical Instrumet Co., China) at 40 °C for 30 min, and

absorbance was recorded at 760 nm. TPC was expressed as mg Gallic Acid Equivalents (GAE) per 100 g of fresh sample (mg GAE/100 g). TPC was calculated using the following formula:

$$\text{TPC}\left(\frac{\text{mg GAE}}{\text{100 g sample}}\right) = \frac{\text{C x V x DF}}{\text{m}}\ x\ 100$$

Where C denotes the concentration of gallic acid based on the calibration curve (mg/ml), V represents the total extract volume used in the reaction (ml), DF is the Dilution Factor, and m is the sample mass (g).

The gallic acid (Sigma-Aldrich, USA) calibration curve was linear over 0-200 µg/ml with R^2=0.998.

Analysis of FSO

-Fatty Acid (FA) compositions

FAs were converted into their methyl esters prior to analysis, according to the Chinese Standard GB 5009.168-2016 (2016). For this process, 2 g of the sample were saponified under a nitrogen atmosphere (99.99% N_2) at 80 ºC for 30 min with 40 ml of 2% NaOH in methanol. FA Methyl Esters (FAME) were obtained by treating the sample with 4 ml of 15% boron trifluoride (BF_3) in methanol (Merck, Germany).

For the Gas Chromatography (GC, Philips, UK) analysis, the FAME samples were injected into a PU 4410 gas chromatograph (Philips, UK) fitted with a 30 m × 0.25 mm × 0.50 µm HP-Innowax capillary column (Agilent, USA).

High-purity nitrogen gas (99.99%) served as the carrier at 1.0 ml/min. The Gas Chromatography (GC) oven was set to increase from 140 ºC to 240 ºC at 4 ºC/min, with a 5-min initial hold at 140 ºC and 15-min final hold at 240 ºC. Samples (1 µl each) were injected with a split ratio of 100:1, while the injector and Flame Ionization Detector were maintained at 250 ºC. FAMEs were characterized by comparing their chromatographic behavior and mass spectra with reference standards, and their relative proportions were expressed as a percentage of the total FAMEs.

-Malondialdehyde (MDA)

MDA levels in the samples were measured following Chinese Standard GB 5009.181-2016 (2016), with minor modifications. Five g of the sample were combined with 50 ml of a trichloroacetic acid solution (T6399, Sigma-Aldrich, USA), which was prepared by dissolving 37.5 g of trichloroacetic acid and 0.5 g of EDTA-Na_2 (E5134, Sigma-Aldrich, USA) in water up to 500 ml. The mixed solutions were then shaken for 30 min at 50 °C using an oscillator (THZ-82B, Shanghai Yiheng Instruments Co., China) and then passed through Whatman No.1 (GE Healthcare, UK) for clarification. Next, 5 ml of the clarified solution were added to 5 ml of thiobarbituric acid (T5500, Sigma-Aldrich, USA; 2.88 g/L) in a 25 ml colorimetric tube, then incubated in a water bath (HH-S6, Jintan Medical Instrument Co., China) at 90 ºC for 30 min to generate a pink-colored complex. After cooling the colorimetric tubes at room temperature for 1 h, absorbance was measured at 532 nm using a UV-1800 spectrophotometer (Shimadzu, Japan). The MDA content was determined from the standard calibration curve (y = 1.0343x + 0.0157, R^2=0.9985) and reported in mg/kg.

-The Peroxide Value (PV)

The PV of the oil samples were measured using Organization for Standardization (ISO) 3960: 2007, which is equivalent to AOAC Official Method 965.33 (AOAC, 2019; ISO 3960, 2007). The Acid Value (AV) was determined following ISO 660: 2009, equivalent to AOAC Official Method 940.28 (AOAC, 2019; ISO 660, 2009), while the Anisidine Value (AnV) was evaluated according to ISO 6885: 2006, corresponding to AOAC Official Method 993.20 (AOAC, 2019; ISO 6885, 2006). Additionally, the Iodine Value (IV) was determined following ISO 3961: 2013, which aligns with AOAC Official Method 920.158, with minor modifications (AOAC, 2019; ISO 3961, 2013).

PV: Approximately 5.0 g of oil was combined with 30 ml of a chloroform-acetic acid solution (3:2, v/v; Merck, Germany) until completely dissolved. Then, 0.5 ml of saturated potassium iodide solution (K1751, Sigma-Aldrich, USA) was combined with the sample and gently agitated in the dark for 1 min. Next, 30 ml of distilled water was introduced, and the liberated iodine was titrated with 0.01 N sodium thiosulfate solution ($Na_2S_2O_3$, S7026, Sigma-Aldrich, USA) using starch solution (S9765, Sigma-Aldrich, USA) as an indicator. The titration was performed using a burette (Brand GmbH, Germany). The PV (meq O_2/kg oil) was calculated using the following equation:

$$\text{PV} = \frac{(V_1 - V_0)\ \text{x N x 1000}}{\text{m}}$$

Where: V_1 is the volume of $Na_2S_2O_3$ used for the sample (ml); V_o is the volume for the blank (ml); N is the normality of $Na_2S_2O_3$; m is the sample mass (g).

AV: Approximately 5 g of the oil sample was dissolved in 50 ml of a neutral ethanol–diethyl ether mixture (1:1, v/v; Merck, Germany). Then, a few drops of phenolphthalein solution (PHR1251, Sigma-Aldrich, USA) were added as an indicator, and the mixture was titrated with 0.1 N KOH solution (P5958, Sigma-Aldrich, USA) until a faint pink color persisted for 30 s. The AV was determined using:

$$\text{AV} = \frac{(\text{V} - V_0)\ \text{x N x 56.1}}{\text{m}}$$

Where V represents the KOH volume used for the sample (ml), V_0 that for the blank (ml), N the KOH normality, m the sample mass (g), and 56.1 the molar mass of KOH.

AV was expressed as mg of KOH per gram of oil required for Free Fatty Acid (FFA) neutralization.

AnV: A 0.5 g oil sample was dissolved in 25 ml of isooctane (M039, Merck, Germany), and the absorbance was recorded at 350 nm (A_1) using a UV-Visible spectrophotometer (UV-1800, Shimadzu, Japan). Then, 1 ml of p-anisidine reagent, containing 2.5 g p-anisidine (A31209, Sigma-Aldrich, USA) dissolved in 100 ml glacial acetic acid (1.00063, Merck, Germany), was added to 5 ml of the isooctane solution. After a 10-min kept in darkness, absorbance (A_2) was measured at 350 nm. The AnV value determined using the expression below:

$$AnV = 25 \times \frac{1.2A_2 - A_1}{m}$$

Where A_1 represents the measured optical response of the oil extract before any treatment, A_2 corresponds to the value obtained after exposure to the p-anisidine solution, and m denotes the sample weight (g).

IV: Approximately 0.3 g of the oil sample was accurately weighted and dissolved in 15 ml of a cyclohexane–glacial acetic acid mixture (1:1, v/v; Merck, Germany). Then, 25 ml of Wijs reagent (W301-100ML, Sigma-Aldrich, USA) was added to the solution and incubate in the dark for about 30 min at room temperature. Next, 10 ml of a 10% potassium iodide solution (K1751, Sigma-Aldrich, USA) was added, followed by 100 ml of distilled water. After gentle shaking and the addition of starch indicaton (S9765, Sigma-Aldrich, USA), the liberated iodine was titrated with 0.1 N sodium thiosulfate solution (S7026, Sigma-Aldrich, USA) until the blue tint faded completely. The IV (g I_2/100 g) determined as shown in the formula below:

$$IV = \frac{(V_1 - V_0) \times N \times 12.69}{m}$$

Where V_1 corresponds to the $Na_2S_2O_3$ volume applied in the titration of the sample (ml), V_o refers to the volume required for the blank (ml), N represents the normality of the $Na_2S_2O_3$ solution, and m is the mass of the oil sample (g). The constant 12.69 represents the conversion factor.

Sensory evaluation

A well-trained and calibrated sensory panel conducted the sensory evaluation of FSO. Twelve panelists (6 males and 6 females), aged from 22 to 35 years, participated in the study. All panelists underwent a two-week training program to familiarize themselves with the sensory attributes of linseed oil, including color, transparency, odor, and flavor, using reference samples established by Wiesenborn *et al.* (2005). Each sample was placed in a transparent 50-ml glass bottle and labeled with a unique random code to ensure that the sensory panelists were unaware of the sample identities. Each panelist carried out the evaluation in an individual sensory booth to minimize potential bias. Sensory parameters, including color, transparency, odor, flavor, and overall acceptability, were evaluated. A hedonic scale with five levels was applied, covering ratings from the lowest (1) to the highest (5).

Statistical analysis

All experimental data were analyzed statistically through SPSS software (v.25.0; IBM Corp., USA). A repeated-measures ANOVA was applied, followed by Bonferroni-adjusted post hoc comparisons to determine significant differences between mean values. All experiments were conducted in six replicates (n = 6). Data are presented as means ± Standard Deviations (SD), with $p<0.05$ indicating statistical significance.

Results and discussion

Effect of microwave roasting on proximate composition of flaxseed

Table 1 shows the proximate composition of flaxseeds. The results showed minor variations in the proximate composition of the two unroasted flaxseed varieties. Specifically, the moisture content of unroasted Golden flaxseeds was marginally greater than that of unroasted Brown flaxseeds. Both varieties exhibited relatively high oil and protein. Carbohydrate content was moderate, fiber content differed between the two varieties, and ash content was similar. Overall, flaxseeds are rich in fats, proteins, and fibers, but relatively low in carbohydrates, consistent with previous studies (Goyal *et al*., 2014). Reported lipid contents range from 37 to 45 g/100 g (Ishag *et al*., 2019; Kajla, Sharma and Sood, 2015), slightly higher than observed in this study. Flaxseed composition varies due to genetics, growing conditions, and processing (Goyal *et al*., 2014; Singh *et al*., 2011).

Further research indicated that microwave roasting (12 min) did not affect fiber, ash, or protein, but significantly decreased moisture (about 43-50%) and increased oil content (about 6-7%), stabilizing after 9 min. No differences were observed between varieties ($p<0.05$). The observed increase in oil during roasting results from moisture loss (Juhaimi *et al*., 2018; Wani *et al.*, 2013). Microwave treatment also enhances oil extraction by disrupting cell walls, increasing porosity, and facilitating oil release (Koubaa *et al.*, 2016). This has been confirmed in apricot kernels, where microwave roasting significantly increased extracted oil compared to raw seeds (Juhaimi *et al.*, 2018; Suri *et al.*, 2020). However, prolonged microwave treatment causes excessive moisture loss, reducing plasticity and increasing brittleness, which can lower extraction efficiency. Oil yield depends on treatment time, solvent, extraction method, seed genetics, initial moisture, and varietal characteristics (Anjum *et al.*, 2006; Koubaa *et al.*, 2016).

Table 1: Effect of roasting on proximate compositions of flaxseeds

Contents (%)	Variety	Control	3 min	6 min	9 min	12 min
Moisture	Golden flaxseed	0.00±6.24 ^{aA}	0.09±5.11 ^{bA}	0.02±4.23 ^{cA}	0.01±3.51^{dA}	0.06±3.57 ^{dA}
	Brown flaxseed	0.01 ±6.02 ^{aB}	0.06±5.67 ^{bB}	0.01±4.62 ^{cB}	0.09±3.11 ^{dB}	0.02±3.03 ^{dA}
Oil	Golden flaxseed	0.15±32.54 ^{aC}	0.16±33.69 ^{bC}	0.07±34.80 ^{cC}	0.06±35.38 ^{dC}	0.03±35.37 ^{dB}
	Brown flaxseed	0.01±33.43 ^{aD}	0.11±34.01 ^{bD}	0.03±35.24 ^{cD}	0.04±36.69 ^{dD}	0.09±36.60 ^{dC}
Protein	Golden flaxseed	0.01±26.20 ^{aE}	0.09±26.31 ^{aE}	0.20±26.20 ^{aE}	0.10±26.50 ^{aE}	0.66±26.27 ^{aD}
	Brown flaxseed	0.06±28.76 ^{aF}	0.01±28.64 ^{bF}	0.04±28.52 ^{cdF}	0.02±28.55 ^{bdF}	0.01±28.62 ^{bE}
Carbohydrate	Golden flaxseed	0.03±26.23 ^{aE}	0.04±26.15 ^{aE}	0.00±26.02 ^{bE}	0.02±26.35 ^{cEG}	0.08±26.16 ^{aD}
	Brown flaxseed	0.01±26.32 ^{aEF}	0.04±26.19 ^{aE}	0.02±26.22 ^{aE}	0.04±26.29 ^{aG}	0.11±26.19 ^{aD}
Ash	Golden flaxseed	0.03±1.93 ^{aG}	0.05±1.92 ^{aG}	0.03±1.95 ^{aG}	0.09±1.86 ^{aH}	0.01±1.95 ^{aF}
	Brown flaxseed	0.02±1.92 ^{aG}	0.06±1.89 ^{aG}	0.06±1.90 ^{aG}	0.04±1.92 ^{aH}	0.01±1.96 ^{aF}
Fiber	Golden flaxseed	0.05±6.86 ^{aH}	0.05±6.82 ^{aH}	0.03±6.81 ^{aH}	0.06±6.40 ^{bI}	0.04±6.68 ^{cG}
	Brown flaxseed	0.06±3.55 ^{aI}	0.06±3.60 ^{abI}	0.03±3.50 ^{aI}	0.01±3.44 ^{bcA}	0.03±3.60 ^{cA}

Each value in the table represents the mean ± standard Deviations (DV; n = 6).
Different lowercase letters indicate significant differences between golden and brown flaxseed oils within the same roasting time, whereas uppercase letters indicate significant differences among roasting times within each flaxseed variety (analyzed by repeated-measures ANOVA followed by Bonferroni-adjusted post hoc test, p<0.05).

Effect of microwave roasting on TC and TPC of flaxseeds

Differences in TC and TPC among seed oils reflects their antioxidant capacities, with tocopherols inhibiting lipid peroxidation and phenolics enhancing PUFA stability (Hashemi *et al.*, 2017; Yang *et al.*, 2018). Therefore, monitoring TC and TPC levels during microwave roasting is essential for evaluating oxidative stability in vegetable oils. Figure 1 shows the changes in TC and TPC levels in FSOs resulting from microwave roasting.

The results in this study from the oil fraction of flaxseeds showed that the total tocopherol level in Golden and Brown FSOs, measured without microwave treatment, was 252.13 mg/kg and 265.55 mg/kg, respectively. The TC in this study was lower than previously reported, with Yang *et al.* (2018) and Kajla, Sharma and Sood (2015) reporting 377.10 and 395.00 mg/kg in flaxseed, respectively.

Fresh Golden and Brown FSOs contained 24.90 and 26.70 mg GAE/100 g TPC, respectively. Reported values vary, with Alu'datt *et al.* (2013) showing lower contents (20.9-35.1 mg/kg) and Kasote (2013) much higher (8-10 g/kg). Microwave roasting for 3 min increased TC and TPC levels, but prolonged roasting (6-12 min) caused thermal degradation, reducing TC by about 56–60% and TPC by about 41-42% (Alu'datt *et al.*, 2013; Rękas, Wroniak and Ścibisz, 2017; Yang *et al.*, 2018). These trends are consistent with Hashemi *et al.* (2017), who observed 31–50% TPC loss in various seed oils after short microwave roasting, while short microwave treatment can enhance TC release and oil antioxidant stability (Koubaa *et al.*, 2016; Yang *et al*., 2018).

This suggests that microwave heating enhances the TC and TPC of FSO during short roasting periods (3 min). However, prolonged exposure decreases these compounds, ultimately reducing the antioxidant activity of FSO.

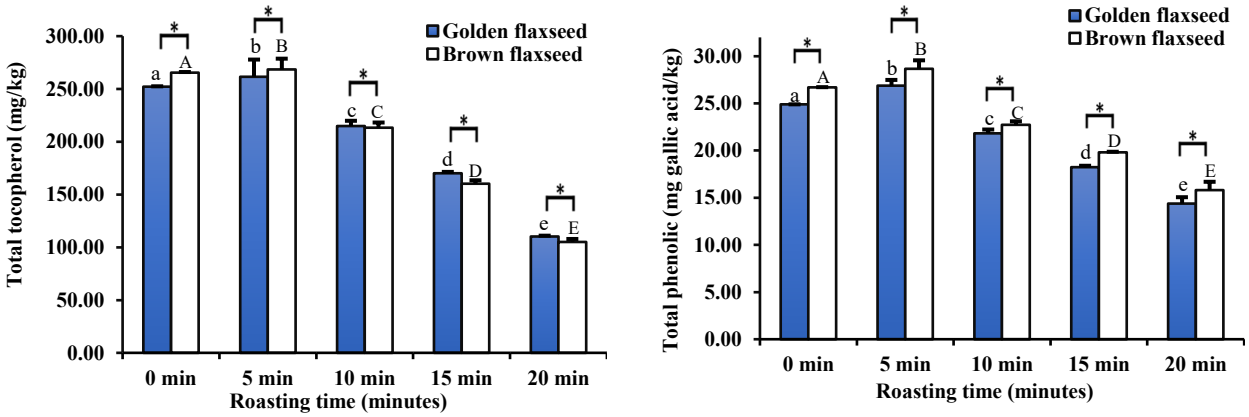

Figure 1: Effect of microwave roasting on the total tocopherol and total phenolic contents of Golden and Brown flaxseeds
Values represent mean ± Standard Deviation (SD; n = 6).
Different lowercase letters (a-e) indicate significant differences among roasting times within Golden flaxseed samples (one-way ANOVA, Tukey's post hoc test, p<0.05).
Different uppercase letters (A-E) indicate significant differences among roasting times within Brown flaxseed samples (p<0.05).
An asterisk (*) denotes a significant difference between Golden and Brown flaxseeds at the same roasting time (Student's t-test, p<0.05).

Effect of microwave roasting on chemical properties of FSOs

Microwave roasting progressively affected the chemical properties of both Golden and Brown FSOs (Figure 2). PV and AnV values increased with roasting time, indicating enhanced primary and secondary oxidation. MDA content also rose, while IV decreased, reflecting a reduction in unsaturated FAs. Overall, these trends demonstrate that prolonged microwave roasting accelerates oxidative changes in FSOs.

PV and AnV: PV measures primary oxidation products, whereas AnV indicates secondary oxidation in oils (Zou *et al.*, 2018). The initial PV values for Golden and Brown flaxseeds were 4.23 and 3.85 meq O_2/kg, respectively, while the initial AnV values were 2.52 and 2.02, respectively. The PV of FSO in this study remained below the Codex limit of 15 meq O_2/kg, consistent with previous reports: Ishag *et al.* (2019) observed 2.69-4.67 meq O_2/kg, Megahed *et al.* (2011) reported PV and AnV of 4.56 meq O_2/kg and 2.63, respectively, while Suri *et al.* (2020) found 2.24 meq O_2/kg in oil from unroasted seeds.

From the obtained results in Figures 2, it can be observed that the changes in both PV and AnV are not significant after 3 min of roasting. PV gradually increased, peaking at 6 min of roasting before declining, consistent with changes in TC and TPC (Figure 1). The early PV rise reflects antioxidant depletion, while the later decline indicates conversion of primary to secondary oxidation products. In contrast, AnV steadily increased throughout roasting, marking progressive secondary oxidation. However, prolonged roasting leads to the decomposition of peroxides into secondary products, such as aldehydes and ketones (Suri *et al.*, 2020). The decline in TC and TPC after 3 min weakens the oil's antioxidant defense, accelerating the degradation of peroxides into secondary oxidation compounds, as indicated by the rising AnV. This inverse relationship demonstrates that antioxidant depletion within the seed matrix directly contributes to enhanced secondary oxidation and reduced oxidative stability. After 12 min of roasting, the PV increases to 5.37 and 4.62 meq O_2/kg, while the AnV rises to 11.28 and 10.21 units in Golden and Brown flaxseeds, respectively. Differences in PV and AnV between the oils may be due to the high PUFA content, especially linolenic acid, which is susceptible to heat-induced oxidation. Microwave roasting has been shown to affect seed and oil chemistry by oxidizing unsaturated FAs, altering PV and AnV, and reducing natural antioxidants such as phenolics and tocopherols, thereby affecting oil stability and quality (Anjum *et al*., 2005; Hashemi *et al*., 2017; Rękas, Wroniak and Ścibisz, 2017; Suri *et al.,* 2020).

AV: AV measures the amount of FFA, partly produced by hydrolysis, and is widely used to evaluate oil deterioration (Tenyang *et al*., 2017). Figure 2 shows that the AV of FSO from fresh Golden and Brown seeds is 0.52 and 0.42 mg KOH/g oil, respectively. The AV values in this study were low, below the Codex limit of 4.0 mg KOH/g oil (Codex Alimentarius Commission, 1999, amended 2023), consistent with reports by Symoniuk, Ratusz and Krygier (2017) and Suri *et al*. (2020), indicating minimal triglyceride degradation and high initial oil quality.

With longer roasting durations, the AV of the extracted oils also rose significantly. After 12 min of roasting, the AV in Golden and Brown flaxseeds reached 1.48 and 1.37 mg KOH/g oil, respectively. The elevated FFA levels in the oil could result from microwave-induced hydrolysis of triacylglycerols, which generates both FFA and diacylglycerols (Anjum *et al.*, 2006). These findings are consistent with previous reports: Ishag *et al.* (2019) observed AVs of 0.75–0.76 mg KOH/g in FSO, Megahed (2011) reported an increase from 0.57 to 1.72 mg KOH/g after 5 min of microwave treatment, and Anjum *et al.* (2006) reported higher FFA levels in roasted sunflower oil. Similar AV increases upon microwave roasting have been reported for poppy seed and FSOs (Seedea, 2025; Suri *et al.*, 2020).

IV: IV indicates the degree of unsaturation in oil and its susceptibility to oxidation. The IV of the extracted oils from Golden and Brown flaxseeds is 95.23 and 95.24 g I_2/100 g of oil, respectively. These results are consistent with Ishag *et al.* (2019), who reported an IV of 97.24 g I2/100 g in FSO, while Megahed (2011) reported a much higher value of 184.0 g I2/100 g. The IV of oils extracted from both flaxseed varieties gradually declined with increasing roasting duration. This decrease may result from the loss of double bonds through oxidation, polymer formation, or the degradation of long-chain FAs. Anjum *et al.* (2006) reported a significant reduction in IV for sunflower and peanut oils as a result of roasting.

MDA value: The MDA represents one of the major aldehydes produced during secondary lipid oxidation. Thiobarbituric Acid Reactive Substances (TBARS) are expressed in terms of MDA equivalents (mg/kg oil) (Symoniuk, Ratusz and Krygier, 2017). The MDA values of unroasted flaxseeds are 0.04 mg/kg in Golden flaxseed and 0.02 mg/kg in Brown flaxseed. These values increased as the roasting period lengthened. Yoshida *et al.* (2006) reported that prolonged roasting led to an increase in MDA levels in pumpkin oil.

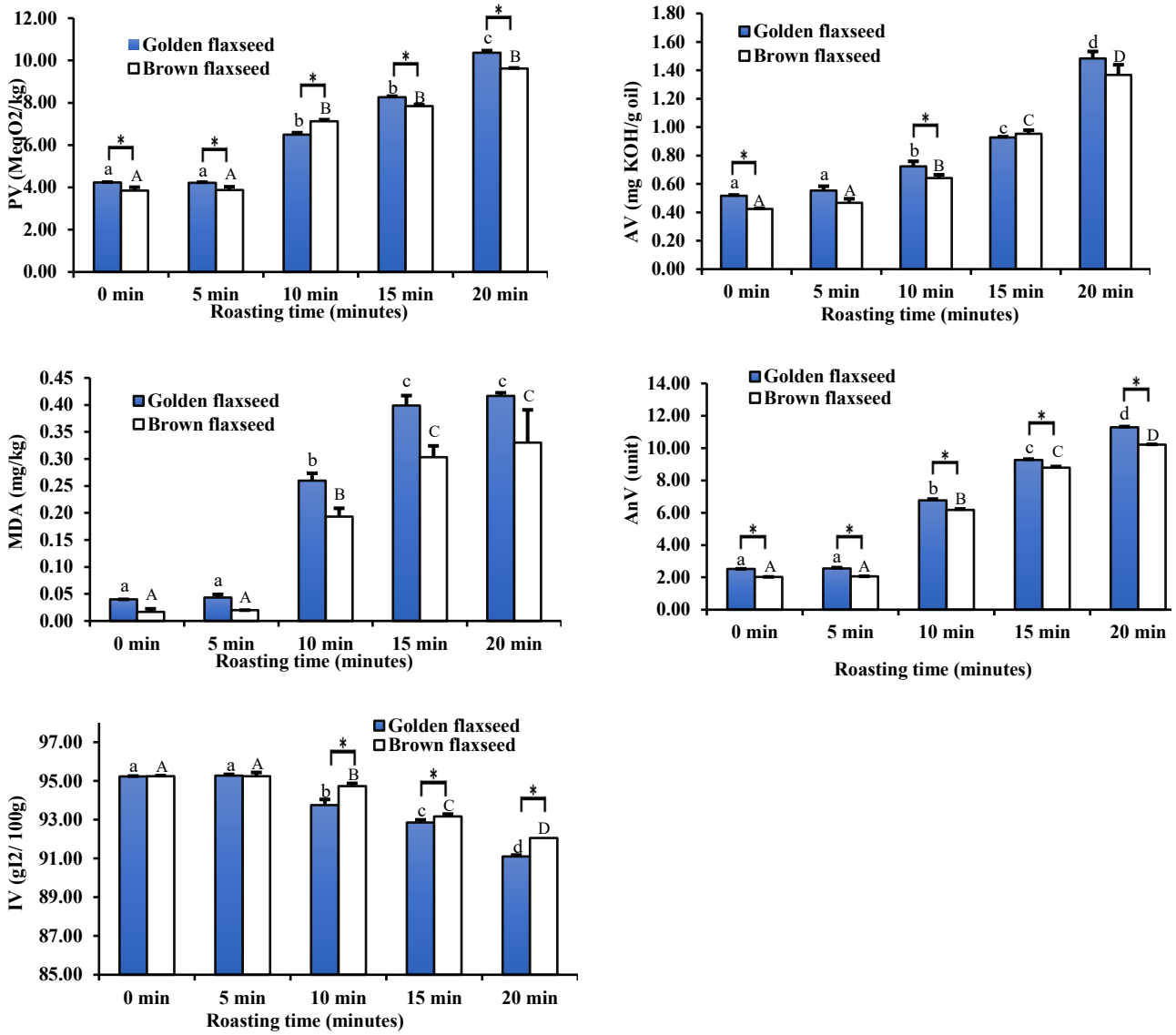

Figure 2: Effect of microwave roasting on the chemical properties (PV, AV, AnV, IV, and MDA) of Golden and Brown flaxseed oils
Values represent mean ± Standard Deviation (SD; n = 6).
Different lowercase letters (a-e) indicate significant differences among roasting times within the same flaxseed variety (one-way ANOVA, Tukey's post hoc test, $p<0.05$).
Different uppercase letters (A-E) indicate significant differences between Golden and Brown flaxseed oils at the same roasting time ($p<0.05$, Student's t-test).
All quantitative data for PV, AV, AnV, IV, and MDA at each roasting time (Control, 3, 6, 9, and 12 min) are presented in this figure for both Golden and Brown flaxseed oils.
Anv=Anisidine Value; AV=Acid Value; IV=Iodine Value; MDA=Malondialdehyde; PV=Peroxide Value

Oxidative parameters (PV, AnV, and MDA) showed an inverse relationship with TPC and TC (Figure 1). During short roasting (3 min), high antioxidant levels helped maintain low oxidation, demonstrating their protective role. Roasting beyond 6 min caused antioxidant breakdown, leading to a marked increase in both primary and secondary lipid oxidation products. This inverse relationship suggests that the reduction in TPC and TC directly contributed to the increase in PV, AnV, and MDA values. Similarly, Hashemi *et al.* (2017), Rękas, Wroniak and Ścibisz (2017), and Suri *et al.* (2020) also demonstrated that the loss of natural antioxidants during thermal or microwave processing markedly enhanced the oxidative deterioration of seed oils.

Although oxidative indices (PV, AnV, AV, and MDA) increased with prolonged roasting, antioxidant activity did not follow the same trend. This may result from simultaneous lipid oxidation and heat-induced release of bound antioxidants. Moderate roasting enhances antioxidant activity by releasing phenolics and tocopherols, while prolonged heating degrades these compounds and increases lipid oxidation, as reported in thermally

processed oils (Hashemi *et al.*, 2017; Suri *et al.*, 2020). Microwave roasting significantly changed the chemical properties of both FSOs. Changes were slight after 3 min but became more pronounced with longer roasting. Despite high unsaturated FA content, oxidative deterioration remained limited up to 12 min, likely due to elevated antioxidant levels in flaxseed (Ishag *et al.*, 2019). The two flaxseed varieties showed similar responses, probably because of comparable chemical compositions.

Effect of microwave roasting on the FA compositions (%) of FSO

Table 2 shows the FA composition of the extracted FSOs.

Previous studies reported varying FA profiles in FSOs. While Golden FSO is rich in linolenic (48.13%), oleic (24.28%), and linoleic (15.43%) acids (Choe and Min, 2007; Singh *et al.*, 2011; Yang *et al.*, 2018), Ishag *et al*. (2019) observed lower linolenic (36.22%) and higher oleic (31.23%) contents in yellow flaxseed. In Brown FSO, linolenic (36.22%), oleic (31.04%), and linoleic (13.23%) acids predominated, in contrast Morris (2007) reported 50.9% linolenic and 14.6% linoleic acids. Such variations are likely due to genetics, environmental conditions, and extraction methods (Ishag *et al*., 2017).

Microwave roasting significantly altered the FA profiles of both FSOs. Roasting for 3 min caused only slight changes, but longer heating decreased PUFAs (linolenic and linoleic acids) and slightly reduced oleic acid, while saturated FAs (palmitic and stearic acids) increased. Total Saturated Fatty Acids (SFA) content rose by about 88% in Golden and 49% in Brown FSOs, whereas total PUFAs decreased by about 14-15%. These changes indicate the progressive oxidation of unsaturated FAs and a relative enrichment of saturated species during roasting. The changes in FA composition in FSOs can be attributed to the impact of microwave energy on PUFAs. Although linolenic acid (C18:3) is highly thermolabile, the relatively moderate microwave intensity and short exposure time (≤12 min) used in this study likely limited its oxidative breakdown and polymerization, resulting in a moderate overall PUFAs reduction (14.3 to 14.8%) despite a noticeable increase in Saturated Fatty Acids (SFA). PUFAs, rich in double bonds, are prone to oxidation under heat, leading to reduced contents (Pop, 2018; Yoshida *et al*., 2006).

These findings align with previous studies on FA oxidation in oil seeds during heating. Microwave roasting slightly altered the FA profile of FSO (Suri *et al.*, 2020). Similarly, prolonged microwave treatment decreased linoleic acid and increased oleic, palmitic, and stearic acids in pumpkin seed oil (Yoshida *et al*., 2006), while in sunflower oil, linoleic acid decreased from 17% to 19% and oleic acid increased from 16% to 42%, with palmitic and stearic acids largely unaffected (Anjum *et al.*, 2006). Despite being an unsaturated FA, oleic acid levels increase under these conditions. The differences observed in existing literature can be attributed to variations in microwave treatment durations and the antioxidant content of raw oil samples.

Table 2: Effect of microwave roasting on the fatty acid composition (% of total fatty acids) of Golden and Brown flaxseed oils

Fatty acid	Variety	Control	3 min	6 min	9 min	12 min
C14:0 (Myristic acid)	Golden	0.00±0.20 ^{aC}	0.06±0.20 ^{bC}	0.00±0.44 ^{aB}	0.02±0.51 ^{aB}	0.03±0.96 ^{aA}
	Brown	0.02±0.31 ^{aB}	0.04±0.34 ^{aB}	0.01±0.32 ^{bB}	0.02±0.51 ^{aA}	0.02±0.63 ^{bA}
C16:0 (Palmitic acid)	Golden	0.01±7.28 ^{bD}	0.13±7.28 ^{bD}	0.01±8.12 ^{bC}	0.07±9.95 ^{bB}	0.01±10.83 ^{bA}
	Brown	0.00±10.18 ^{aC}	0.01±10.41 ^{aC}	0.05±11.04 ^{aC}	0.02±12.56 ^{aB}	0.01±13.82 ^{aA}
C16:1 (Palmitoleic acid)	Golden	0.00±0.13 ^{aA}	0.07±0.12 ^{aA}	0.02±0.21 ^{aA}	0.03±0.23 ^{aA}	0.01±0.27 ^{aA}
	Brown	0.00±0.09 ^{aA}	0.00±0.08 ^{aA}	0.02±0.09 ^{bA}	0.01±0.07 ^{bA}	0.01±0.05 ^{bA}
C17:0 (Marganic acid)	Golden	0.00±0.16 ^{aC}	0.01±0.17 ^{aC}	0.01±0.21 ^{aC}	0.00±0.64 ^{aB}	0.00±0.98 ^{aA}
	Brown	0.00±0.13 ^{aB}	0.01±0.15 ^{aB}	0.00±0.17 ^{aB}	0.01±0.23 ^{bB}	0.01±0.36 ^{bA}
C18:0 (Stearic acid)	Golden	0.00±4.03 ^{bD}	0.02±4.03 ^{bD}	0.00±5.98 ^{bC}	0.01±6.82 ^{bB}	0.02±7.95 ^{bA}
	Brown	0.01±8.31 ^{aC}	0.03± 8.27 ^{aC}	0.00±9.03 ^{aC}	0.05±11.17 ^{aB}	0.02±12.97 ^{aA}
C18:1 (Oleic acid)	Golden	0.00±24.28 ^{bA}	0.37±24.27 ^{bA}	0.05±23.89 ^{bA}	0.13±23.71 ^{bA}	0.05±23.66 ^{bA}
	Brown	0.02±31.04 ^{aA}	0.16±31.01 ^{aA}	0.01±30.84 ^{aA}	0.00±30.15 ^{aA}	0.02±29.06 ^{aA}
C18:2 (Linoleic acid)	Golden	0.01±15.43 ^{aA}	0.10±15.41 ^{aA}	0.00±14.50 ^{aB}	0.02±14.13 ^{aB}	0.04±13.28 ^{aB}
	Brown	0.41±3.23 ^{aA}	0.03±13.23 ^{bA}	0.01±12.75 ^{bB}	0.04±11.83 ^{bC}	0.05±10.91 ^{bD}
C20:0 (Arachidic acid)	Golden	0.00±0.23 ^{aC}	0.00±0.25 ^{aC}	0.01±0.42 ^{aB}	0.01±0.42 ^{aB}	0.01±0.53 ^{aA}
	Brown	0.01±0.24 ^{aC}	0.00±0.23 ^{aC}	0.02±0.23 ^{bC}	0.01±0.45 ^{aB}	0.01±0.65 ^{aA}
C18:3 (Linolenic aicd)	Golden	0.01±48.13 ^{aA}	0.03±48.15 ^{aA}	0.07±46.10 ^{aB}	0.04±43.45 ^{aC}	0.00±41.22 ^{aD}
	Brown	0.03±36.22 ^{bA}	0.03±36.02 ^{bA}	0.04±35.23 ^{bB}	0.06±32.72 ^{bC}	0.01±31.06 ^{bD}
C20:1 (Gondonic acid)	Golden	0.00±0.08 ^{aA}	0.00±0.07 ^{aA}	0.00±0.07 ^{aA}	0.01±0.06 ^{aA}	0.02±0.05 ^{aA}
	Brown	0.00±0.12 ^{aA}	0.00±0.11 ^{aA}	0.03±0.12 ^{aA}	0.00±0.09 ^{aA}	0.00±0.08 ^{aA}
C22:0 (Behenic acid)	Golden	0.00±0.05 ^{aB}	0.00±0.05 ^{bB}	0.01±0.07 ^{bB}	0.01±0.08 ^{aB}	0.01±0.27 ^{bA}
	Brown	0.03±0.13 ^{bB}	0.01±0.15 ^{aB}	0.00±0.18 ^{aB}	0.03±10.23 ^{aB}	0.01±0.41 ^{aA}
SFA total	Golden	0.06±11.67 ^{e}	0.07±11.86 ^{d}	0.06±13.81 ^{c}	0.08±16.29 ^{b}	0.10±21.95 ^{a}
	Brown	0.08±18.93 ^{e}	0.09±19.37 ^{e}	0.07±20.52 ^{d}	0.06±22.98 ^{c}	0.11±28.23 ^{a}
MUFA total	Golden	0.06±24.41 ^{a}	0.05±24.37 ^{a}	0.05±24.05 ^{a}	0.04±22.70 ^{b}	0.04±22.22 ^{b}
	Brown	0.05±31.13 ^{a}	0.04±31.06 ^{a}	0.05±29.76 ^{b}	0.05±28.22 ^{c}	0.06±27.30 ^{d}
PUFA total	Golden	0.05±63.56 ^{d}	0.05±63.28 ^{d}	0.05±60.94 ^{b}	0.06±58.47 ^{c}	0.05±54.45 ^{d}
	Brown	0.06±61.29 ^{a}	0.05±61.04 ^{a}	0.05±58.97 ^{b}	0.05±55.71 ^{c}	0.06±52.21 ^{d}

Each value in the table represents the mean ± Standard Deviations (DV; n=6).
Different lowercase letters indicate significant differences between golden and brown flaxseed oils within the same roasting time, whereas uppercase letters indicate significant differences among roasting times within each flaxseed variety (analyzed by repeated-measures ANOVA followed by Bonferroni-adjusted post hoc test, $p<0.05$).
MUFA=Monounsaturated Fatty Acid; PUFA=Polyunsaturated Fatty Acid; SFA=Saturated Fatty Acid

Effects of microwave roasting on the sensory properties of FSO

The effects of different roasting treatments on the sensory evaluation scores of FSO are showed in Figure 3. The distinct flavors of different oils are influenced by variations in the quantity and quality of their FAs (Tuncel, Uygur and Karagül Yüceer, 2017).

The sensory evaluation of the analyzed linseed oils showed that the scores for color, clarity, aroma, taste, and overall acceptability varied from 1.0 to 4.6. These scores correspond to classifications from “bad” to “good” on the 1 to 5 scale presented in Table 3. Thus, microwave roasting significantly affects the sensory quality of FSO. Both types of FSO achieve the highest sensory scores at 3 min of roasting. However, beyond this point, the sensory scores decline rapidly with increasing roasting time. By the end of the roasting process (12 min), all sensory indicators are rated very low, ranging from 1.0 to 1.3.

Linseed oils microwaved for 3 min showed the highest aroma, taste, and odor scores, likely due to mild Maillard and Strecker reactions producing flavor-active heterocyclic compounds such as pyrazines, pyrroles, and pyridines (Wei *et al.*, 2019). Longer roasting reduced sensory quality, as continued Maillard reactions intensified color, and the high linolenic acid content, 48.13% in Golden and 36.22% in Brown, increased susceptibility to oxidative rancidity, generating off-flavors and lowering overall acceptability. Linolenic acid, which contains three double bonds, is more prone to oxidation than linoleic acid, Monounsaturated Fatty Acids (MUFAs), and oleic acid, explaining the progressive darkening of linseed oil from light yellow to deep brown during roasting (Wei *et al.*, 2019). Oxidation of linseed oil obtained by cold pressing has been associated with the generation of bitter compounds and a decline in its sensory attributes (Symoniuk, Ratusz and Krygier, 2017; Wiesenborn *et al.*, 2005).

Therefore, further research is necessary to clarify how microwave treatment affects the composition of specific FAs in seed oils.

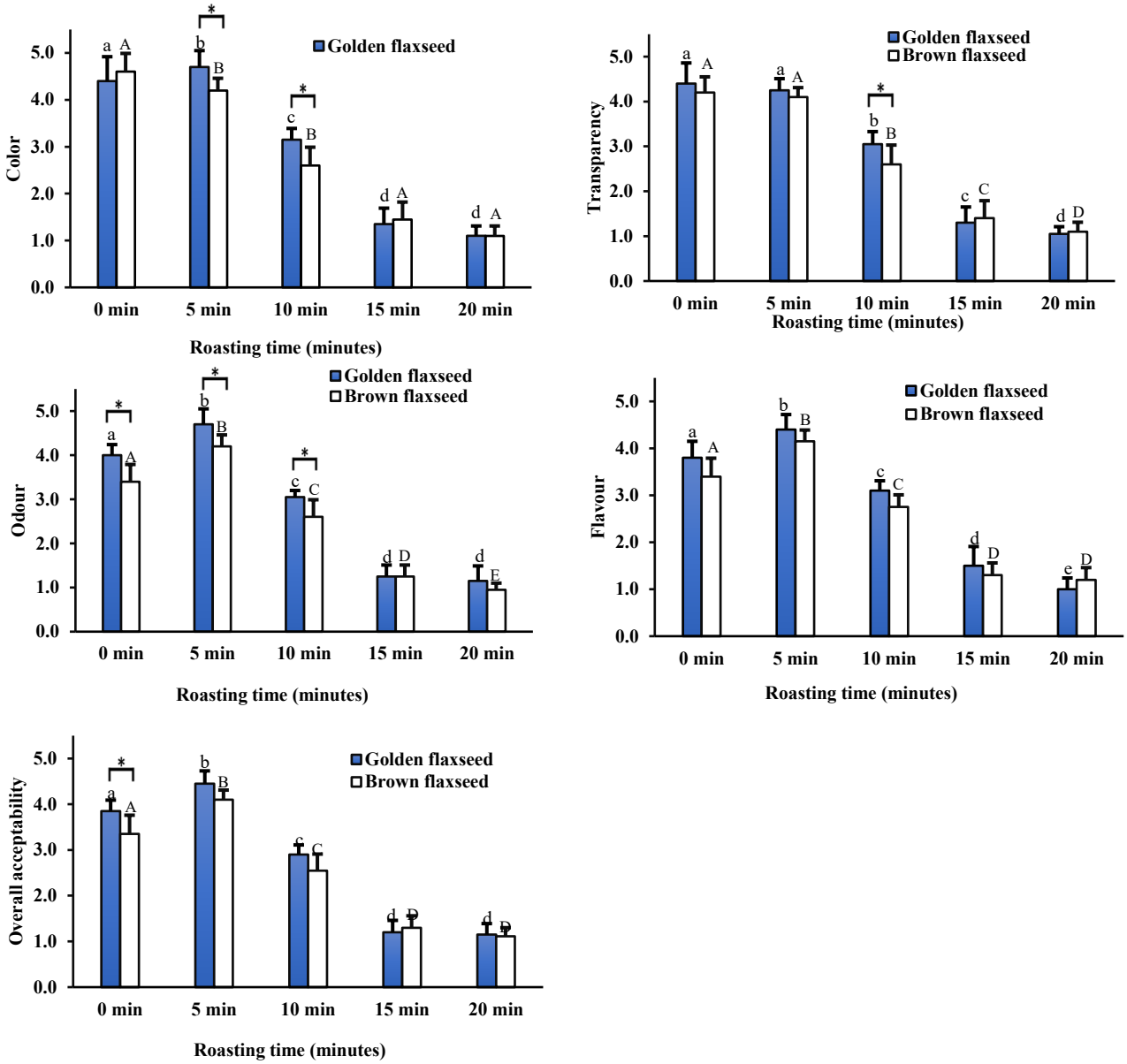

Figure 3: Effect of microwave roasting on the sensory properties of Golden and Brown flaxseed oils
Values represent mean ± Standard Deviation (DV; n = 12).
Different lowercase letters (a-e) indicate significant differences among roasting times within Golden flaxseed oil samples (one-way ANOVA, Tukey's post hoc test, $p<0.05$).
Different uppercase letters (A-e) indicate significant differences among roasting times within Brown flaxseed oil samples ($p<0.05$).
An asterisk (*) denotes a significant difference between Golden and Brown flaxseed oils at the same roasting time (Student's t-test, $p<0.05$).

Conclusion

Microwave roasting significantly influenced the constituents, oxidative stability, and sensory properties of Golden and Brown FSOs. While longer roasting durations intensified oxidation and reduced nutritional quality through the loss of PUFAs and natural antioxidants (tocopherols and phenolics), short-term roasting (around 3 min) enhanced sensory acceptability without severely compromising oxidative stability. This indicates that mild microwave roasting can be a practical processing strategy for producing nutritionally stable FSO with appealing flavor attributes. From an industrial perspective, adopting optimized short-duration roasting could improve oil extraction efficiency and sensory quality while maintaining a favorable FA profile for health-promoting applications. Further research should explore the molecular mechanisms underlying antioxidant degradation and the scalability of microwave roasting for FSO production.

Author contributions

T.T.L. and L.Y. conceptualized the study; T.T.L. and G.S. designed the methodology; T.T.L. and P.T.V.

performed the formal analysis; G.S. validated the results; T.T.L. prepared the original draft; G.S., T.T.L., and P.T.V. reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Conflicts of interest

The Authors declare that there is no conflict of interest.

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Ethical considerations

Not applicable.

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