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Improvement of thermo-resistance and quality of soybean oil by blending with cold-pressed oils using simplex lattice mixture design☆

Aicha Benbouriche[1,*], Hayate Haddadi-Guemghar[1], Mostapha Bachir-bey[2], Lila Boulekbache-Makhlouf[1], Samir Hadjal[3], Louiza Kouadri[3], Djamila Mehidi-Terki[4], Morad Hamitri[4] and Khodir Madani[1,5]

[1] Laboratoire de Biochimie Biophysique Biomathématique et Scientométrie, Faculté des Sciences de la Nature et de la Vie, Université de Bejaia, 06000 Bejaia, Algérie
[2] Laboratoire de Biochimie Appliquée, Faculté des Sciences de la Nature et de la Vie, Université de Bejaia, 06000 Bejaia, Algérie
[3] Laboratoire recherche et développement, Complexe agro-alimentaire de CEVITAL Agro-industrie, Nouveau Quai, Port de Bejaia, 06000 Bejaia, Algérie
[4] Laboratoire central des corps gras, Complexe agro-alimentaire de CEVITAL Agro-industrie, Nouveau Quai, Port de Bejaia, 06000 Bejaia, Algérie
[5] Centre National de Recherche en Technologies Agroalimentaires, route de Targa-Ouzemour, 06000 Bejaia, Algérie

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Abstract – Soybean oil is the most consumed oil worldwide due to its cheapness but presented a weak thermo-resistance due to its richness in poly-unsaturated fatty acids. This study aims to improve the thermo-stability of refined soybean oil by blending it with some cold-pressed oils. For this, cold-pressed and soybean oils were firstly characterized (K_{232}, K_{270}, acidity, peroxide value, iodine value, induction time, phenolic contents, and antioxidant activity). Then, binary blends of each cold-pressed oil (30%) with soybean oil (70%) were analyzed before and after heat treatment (170 °C for 10 h/day for 5 days) followed by the application of the simplex lattice mixture design in order to optimize the combination of the three best cold-pressed oils. The changes in fatty acid profiles were assessed by gas chromatography (GC-FID). The results revealed that soybean oil presented the best physicochemical traits, while cold-pressed oils expressed high levels of phenolic contents and antioxidant activities. From the six binary oil blends, soybean oil mixed with lentisk, sesame, or almond oils were selected for their best thermo-stability. The simplex lattice mixture design, applied for these three chosen oils, indicated that the combination of soybean oil (70%) with lentisk and sesame oils (17.7 and 12.3%, respectively) was considered the optimal blend that gives the maximal thermo-stability improvement to soybean oil. GC-FID analysis showed that fatty acids, particularly linoleic and linolenic acids, were more conserved after heat-treatment in optimal oils blend than soybean oil. This study clearly demonstrated that lentisk and sesame oils enhanced the thermo-resistance of soybean oil, and the findings of this study could be used as an integrated model in oil and fat industries.

Keywords: soybean oil / cold-pressed oil / thermo-stability / fatty acids composition / simplex lattice mixture design

Résumé – Amélioration de la thermo-résistance et de la qualité de l'huile de soja par coupage avec des huiles pressées à froid en utilisant un plan de mélange en réseau centré. L'huile de soja est l'huile la plus consommée dans le monde en raison de son faible coût, mais présente une faible thermo-résistance en raison de sa richesse en acides gras polyinsaturés. Cette étude vise à améliorer la thermo-stabilité de l'huile de soja raffinée par coupage avec quelques huiles pressées à froid. Pour cela, les huiles pressées à froid et l'huile de soja sont d'abord caractérisées (K_{232}, K_{270}, acidité, indice de peroxyde, indice d'iode, temps d'induction, teneurs phénoliques et activité antioxydante). Ensuite, des mélanges binaires de chaque huile pressée à froid (30%) avec l'huile de soja (70%) sont analysés avant et après le traitement thermique (170 °C

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*Correspondence: aicha.benbouriche@univ-bejaia.dz

durant 10 h/jour pendant 5 jours) suivi de l'application du plan de mélange (plan de mélange en réseau centré) afin d'optimiser la combinaison des trois meilleures huiles pressées à froid. Les modifications des profils d'acides gras ont été évaluées par chromatographie en phase gazeuse (GC-FID). Les résultats révèlent que l'huile de soja présente les meilleures caractéristiques physicochimiques, tandis que les huiles pressées à froid expriment des niveaux élevés de contenus phénoliques et d'activités antioxydantes. Parmi les six mélanges d'huiles binaires, l'huile de soja mélangée avec les huiles de lentisque, de sésame ou d'amande sont sélectionnée pour leurs meilleures thermo-stabilités. Le plan de mélange, appliqué pour ces trois huiles choisies, indique que la combinaison d'huile de soja (70 %) avec les huiles de lentisque et de sésame (17,7 et 12,3 %, respectivement) est considérée comme le mélange optimal qui donne l'amélioration maximale de la stabilité thermique à l'huile de soja. L'analyse GC-FID a montré que les acides gras, en particulier les acides linoléique et linolénique, sont mieux conservés après le traitement thermique dans le mélange d'huiles optimal que dans l'huile de soja. Cette étude montre clairement que les huiles de lentisque et de sésame améliorent la thermo-résistance de l'huile de soja et que les résultats de cette étude peuvent être utilisés comme modèle intégré dans les industries des huiles et graisses.

Mots clés : huile de soja / huile pressée à froid / thermo-stabilité / composition en acides gras / plan de mélange en réseau centré

1 Introduction

In recent times, there is a growing interest from agri-food industries in different variety of oleaginous resources to provide a wide range of fats and oils with valuable properties. These fats/oils must simultaneously meet many expectations, like providing high nutritional quality, a nice soft texture, and a resistance to cooking temperature (Morin and Pagès-Xatart-Parès, 2012).

The quality of oils can be evaluated by some physico-chemical tests. Peroxide value and UV absorption coefficient can be taken as a picture of the oxidative state, while the amount of acidity reveals some information about the oil quality. Iodine number provides the degree of lipids unsaturation that are related to oxidative stability and rancidity of the oil. Likewise, rancimat test, antioxidant activity, and total phenolic compounds (TPC) informed on the degree of oil resistance to oxidation. The study of all these parameters could successfully guide the selection of better oils and oils mixture.

Soybean oil is one of the most used oils throughout the world. In 2019, the total world production of soybean is estimated at 333 million tons (Faostat, 2021). The crude soybean oil has highly nutritious properties and it may protect against some cancers like breast and prostate cancers, but cannot be used for cooking purposes due to its unpleasant smell (Li *et al.*, 2014; Thakkar and Parikh, 2014), therefore soybean oil needs a refining step. The refining process of vegetable oil is conducted in order to discard undesirable components to obtain refined oil with ameliorated stability, attractive color, and acceptable smell with adequate preferences for consumers (Chew and Ali, 2021). During oil refining, some parameters are ameliorated (decrease in UV absorption coefficients, acidity, color, wax level) while others are affected (decrease of unsaponifiables, tocopherols, sterols, phenolic compounds) resulting a soybean oil with lower oxidative stability (Gharby *et al.*, 2021; Atta and Al-Okaby, 2022). Despite its high thermal degradation, refined soybean oil remains widely used as all-purpose cooking oil with acceptable nutritive value (Prabsangob and Benjakul, 2018).

During frying or cooking, lipids of edible oils undergo oxidation that is responsible for the loss of their quality. During lipid oxidation, some toxic products were formed, initially primary oxidation products (alkoxy and peroxy radicals, and hydroperoxides) then secondary compounds (aldehydes, ketones, and carbonyl components) that may often result in a certain number of adverse effects (Osório and Cardeal, 2013; Fadda *et al.*, 2022). The oxidation of lipids depends upon external factors including temperature, time, and oxygen as well as internal factors such as unsaturation degree, and the presence of antioxidant compounds, or certain metals (Fadda *et al.*, 2022).

Numerous edible oils are naturally protected by their endogenous antioxidants (tocopherols and phenolic compounds), while some others (like soybean oil) are more susceptible to oxidation due to the refining process; they undergo and need to be enriched with exogenous antioxidants. The latter consists of adding synthetic chemicals antioxidants (tert-butylhydroquinone, propyl gallate, butylated hydroxyanisole, and butylated hydroxytoluene), natural plant extracts rich mainly in carotenoids, α-tocopherol, and polyphenols, or provided from other oils by blending (Fadda *et al.*, 2022).

The blending of vegetable oils is one of the most widely used practices in the oil industry to produce oil blends with enhanced stability, good nutritional value, and suitable sensory properties (Bordón *et al.*, 2019). Mixing different vegetable oils can change fatty acids composition and give higher levels of natural antioxidants and bioactive lipids in the blends and, therefore, can improve the nutritional value and stability of oils (Bordón *et al.*, 2019; Nanayakkara *et al.*, 2020; Farag *et al.*, 2021). The oil blends could contribute as sources of important antioxidants related to the prevention of chronic diseases associated with oxidative stress, such as cancer and coronary diseases (Li *et al.*, 2014).

Some studies demonstrated that soybean oil blended with other cold-pressed oils improved its quality. The heat treatment (180 °C/5 days) of soybean oil blended with camellia oil (90:10 to 50:50) demonstrated weak changes in fatty acid compositions and an increase in oxidative stability due to the high content of phenolic compounds and monounsaturated fatty acids of camellia oil, while soybean oil alone manifested highest deterioration (Wang *et al.*, 2016). Soybean oil frying showed an increased formation of primary oxidation compounds and a decrease in oxidative stability. The addition of melon or papaya oil to soybean oil (20:80) showed amelioration in physicochemical parameters and increased the nutritional value and stability of soybean oil (Veronezi and Jorge, 2018). The formulation of frying oil by blending of soybean oil with sesame oil at a ratio of 60:40 allowed reducing its viscosity, making it desirable for cooking purposes, and offering protection from acidity development by 10% (Garg *et al.*, 2021).

Accordingly, many healthy edible oils with high nutritional quality and phytochemical contents can be blended with soybean oil (such as camellia, sesame, and peanut oils) in order to ameliorate oil properties. Almond oil, for example, is used in the food industry; its excellent nutritional and organoleptic qualities make it beneficial for many health-related aspects (Ouzir *et al.*, 2021; Sakar *et al.*, 2021). Nigella oil contains high levels of tocopherols so good antioxidant activity (Karoui *et al.*, 2020). Lentisk oil presents an adequate content of unsaturated fatty acids and it is very rich in natural antioxidants particularly polyphenols (Brahmi *et al.*, 2020). The oil extracted from peanuts presents good bioactivity and nutritional value (Ciou *et al.*, 2021). Sesame oil is endowed with excellent thermo-oxidative stability because of its richness in bioactive lignans (sesamolin, sesamol, sesamin) and its balanced ratio of ω-fatty acids (ω6 and 9) (Hemalatha and Ghafoorunissa, 2007; Ghosh *et al.*, 2019). Wild olive or oleaster oil is largely distributed all around the Mediterranean basin and is known for its antioxidants (tocopherol and phenolic compounds) (Bouarroudj *et al.*, 2016; Djelloul *et al.*, 2020). This study was distinguished by applying the screening of some binary blending between cold-pressed oils and soybean oil and then formulating the optimal blend by using an experimental design.

In this regard, the present investigation was carried out to improve the thermo-resistance of soybean oil using a blending with cold-pressed oils. Firstly, the studied oils (refined soybean and six cold-pressed oils: almond, lentisk, nigella, peanut, sesame, and wild-olive oils) were assessed individually. After that, the binary blends of soybean oil with each of the six oils (70:30, v/v) were investigated. Finally, the three selected best oils were combined through a simplex lattice mixture design to optimize a better blend that improves the thermal resistance and quality parameters of soybean oil.

2 Materials and methods

2.1 Reagents

Phenolphthalein, potassium hydroxide, potassium iodide, sodium thiosulfate, Wijs reagent, ABTS (2.2'-azino-bis-(3-ethylbenzthiazoline-6-ulfonic acid)), sodium carbonate, potassium persulfate, gallic acid, and Folin–Ciocalteu reagent were from Sigma–Aldrich (Germany). Fatty acid methyl esters (FAME) standards were purchased from Supelco (USA). All used solvents were at analytical grade and procured from Prolabo (France).

2.2 Vegetable oil samples

The sample of refined soybean oil was obtained from Cevital Company (Bejaia, Algeria) in PET bottles of 1 L. Six cold-pressed oils extracted from almond (*Prunus dulcis*), lentisk (*Pistacia lentiscus*), nigella (*Nigella sativa*), peanut (*Arachis hypogaea*), sesame (*Sesamum indicum*), and wild-olive (*Olea europaea* subsp. *cuspidate*) were used for blending with soybean oil. The almond, nigella, peanut, and sesame seeds were purchased from specialized grocery stores provided respectively from USA, Syria, Argentina, and India. Lentisk fruits were collected from Bejaia Department (Algeria) in February and then dried under a temperature of about 25 °C in order to remove humidity and facilitate the extraction. The wild-olive fruits were harvested from Tizi-Ouzou Department (Algeria) in December. The oils from seeds and dried lentisk fruits were extracted using an oil press (Oleum, UK) at room temperature by the Parapharmaceutical Products and Equipment Manufacturing Company (Bejaia, Algeria). The wild-olive oil was extracted using an automatic olive oil mill. All oils were transported to the laboratory taking into account protective measures against oxidation. Glass flasks of 250 mL were filled with oils and tightly closed in order to remove the air and wrapped in aluminum foil to avoid light, once at the laboratory they were stored at 6 °C until and during use.

2.3 Blending of vegetable oils

In the first step, the studied oils (soybean, almond, lentisk, nigella, peanut, sesame, and wild-olive oils) were individually analyzed in order to determine the initial characteristics. Then, soybean oil was mixed with each of the six cold-pressed oils at a ratio of 70%:30% (v/v). The obtained binary oil blends were analyzed before and after thermal treatment to select the three best oils that improve the thermo-oxidation resistance of soybean oil. In the last step, the three selected best oils from the second experiment were combined according to Simplex Lattice Mixture Design in order to assess the optimal combination of oils that improves the thermo-resistance of soybean oil. The vertices of the equilateral triangle represented the chosen oils (almond, lentisk, or sesame oil) that varied from 0 to 1, the combination binary levels were 1/3, 2/3, and the ternary mixture was represented by the center of the triangle with a combination of the three oils at the level of 1/3 each (Benbouriche *et al.*, 2021). The ten different oil combinations were indicated in Table 3. The analyzed variables or responses were physicochemical parameters (UV absorption coefficient, acidity, peroxide value, iodine value, and rancimat test), total phenolic content, and antioxidant activity. The responses were fitted as a polynomial model according to equation (1);

$$Y = b_1x_1 + b_2x_2 + b_3x_3 + b_{1,2}x_1x_2 + b_{1,3}x_1x_3 + b_{2,3}x_2x_3, \quad (1)$$

where Y is the response; b_1, b_2, and b_3 are the linear terms of the equation, $b_{1,2}$, $b_{1,3}$, and $b_{2,3}$ are the interaction terms of the equation; x_1, x_2, and x_3 are the factors (sesame, lentisk, and almond oils).

2.4 Thermal treatment

The oils obtained from soybean oil mixed with other cold-pressed oils as well as soybean oil alone (as control) were treated with heating. For mixed oil, 70 mL of soybean oil were introduced into a flask and 30 mL of each oil or combined cold-pressed oils were added. The obtained oils mixture was properly homogenized using a magnetic stirrer. The heating container was a glass flask of 120 mL of volume with an internal diameter of 4.77 cm offering an exposed surface of the oil to the air of 17.90 cm^2 and a volume/surface ratio of 5.59. All oils were thermally treated under a temperature of 170 °C for 10 h/day for 5 days. It is worth noting that 20 min were needed to reach the final temperature, and oils were left at room temperature between two cycles. In order to induce oil oxidation, the flasks are left open during the entire treatment period.

2.5 Physicochemical analysis

The physicochemical parameters assessed were UV absorption coefficient at 232 and 270 nm, acidity, peroxide value, and iodine value. The different analyses were performed on soybean oil (control), cold-pressed oils, binary oil blends, and combined oils regarding the simplex lattice mixture design.

2.5.1 UV absorption coefficient

For UV absorption coefficient measurement, 2.5 g of sample oil was adjusted to 25 mL with cyclohexane and homogenized (Hamitri-Guerfi *et al.*, 2020). Absorbance was measured at 232 and 270 nm after an adequate dilution and using a quartz cuvette in a spectrophotometer (Uvline 9400, Secomam, France). The UV absorption coefficient of oil was calculated using the following equation (2);

$$\varepsilon^{1\%}1_{\mathrm{cm}}(\lambda) = A(\lambda)/(C \times d), \tag{2}$$

where $\mathcal{E}^{1\%}{}_{1\mathrm{cm}}(\lambda)$, UV absorption coefficient at a wavelength of 232 or 270 nm; A(λ), absorbance at 232 or 270 nm; C, concentration of analyzed solution in g/100 mL; d, width of spectrophotometer quartz cuvette (cm).

2.5.2 Acidity

Two grams of sample oil were weighted in an Erlenmeyer flask and 100 mL of ethanol/chloroform (1:1, v/v) were added as well as 4 drops of phenolphthalein as colored indicator. The mixture was titrated with potassium hydroxide (KOH, 0.1 N) until the appearance of persistent pink color (Kiritsakis and Markakis, 2012). The acidity (Ac) was expressed in percentage of oleic acid equivalent per 100 g of oil using equation (3);

$$A_c(\%) = (V \times N V 282.2) \times 100/(w \times 1000), \tag{3}$$

where A_C (%), acidity in percentage; *V*, volume of KOH solution used (mL); *N*, normality of KOH solution (0.1 N); *282.2*, molecular weight of oleic acid (mol/L); *w*, weight of oil aliquot (g).

2.5.3 Peroxide value

The peroxide value of oils was measured according to Novidzro *et al.* (2019). An aliquot of oil (2 g) was weighed in an Erlenmeyer flask then 15 mL of acetic acid and 1 mL of saturated potassium iodide solutions were added. After putting the cap, the flask was shaken for 1 min and then stands for exactly 5 min in obscurity. 75 mL of distilled water were added then the mixture was titrated with sodium thiosulfate solution (0.02 N) using starch solution as a color indicator. A blank test was simultaneously carried out containing all reagents with the exception of oil. The peroxide value (PV) was expressed in milliequivalents of active oxygen per kilogram of oil (meq O_2/kg oil) and calculated following equation (4);

$$PV = (V \times N \times 1000)/w, \tag{4}$$

Where *PV*, peroxide value (meq/kg); *V*, volume of sodium thiosulfate solution used (mL); *N*, concentration of thiosulfate solution (0.02 N); *w*, weight of oil aliquot (g).

2.5.4 Iodine value

A quantity of oil (0.15 g) was dissolved with 15 mL of chloroform in an Erlenmeyer flask. Then, a volume of Wijs reagent (25 mL) was added. The mixture was stirred and placed in the dark for one hour. After that, 20 mL of potassium iodide solution (10%) and 150 mL of water were added to the previous mixture. The iodine released is titrated with sodium thiosulfate (0.1 N) in the presence of starch as an indicator until the medium turns colorless. A blank test was carried out under the same conditions using all elements of the mixture with the exception of oil (Lee *et al.*, 2021). The iodine value was calculated following equation (5);

$$IV = (V_0 - V_s) \times 12.69/w, \tag{5}$$

where *IV*, Iodine value (g I_2/100 g oil); V_0, volume of sodium thiosulfate solution used (mL, 0.1 N) for the blank; V_s, volume of sodium thiosulfate solution used (mL, 0.1 N) for the oil; *w*, weight of oil aliquot (g); *12.69*, concentration conversion coefficient.

2.5.5 Rancimat test

The Rancimat method is an accelerated aging test commonly used for the assessment of oxidative stability of oils or fats. The oxidative stability of the investigated oil samples was tested using the Rancimat apparatus (CH 9100, Methrom, Switzerland). An aliquot of oil (3 g) was subjected to a temperature of 100 °C at an airflow rate of 10 L/h. The measurement was based on the conductimetric detection of volatile acids. The results were expressed as the induction time (IT) in hours, which represents the duration needed for the decomposition of hydroperoxides produced in oil after oxidation under the oxygen and temperature effects (Hasni *et al.*, 2017).

2.6 Phenolic compounds extraction, quantification, and antioxidant evaluation

The extraction of phenolic antioxidants was conducted following Gutfinger (1981) method. Five milliliters of hexane were added to 1 g of oil and then 5 mL of 60% methanol were added. The mixture was vortexed for 3 min and then centrifuged (Nüve NF 200, Ankara, Turkey) at 4000 rpm/5 min. The lower methanolic phase was recovered and the hexanic layer was re-extracted using 5 mL of 60% methanol following the same procedure. The two extractions were combined.

Total phenolic content was determined as described by Bachir bey *et al.* (2014). Folin–Ciocalteu reagent (750 μL) was added to methanolic extract (700 μL) and sodium carbonate (7%, 400μL) was added after 5 min. The absorbance was recorded at 750 nm after 1 h of incubation. The results were expressed as mg gallic acid equivalent per 100 g of oil (mg GAE/100 g oil).

The radical scavenging activity (RSA) was determined by ABTS radical as reported by Lu-Martínez *et al.* (2020). 400 μL of oil extract were mixed with 2 mL of alcoholic solution of $ABTS^{\bullet +}$. The absorbance was measured at 734 nm after 15 min. The percentage of RSA was estimated by following equation (6);

$$RSA(\%) = (A_c - A_s) \times 100/A_c, \qquad (6)$$

where A_c, absorbance of control; A_s, absorbance of sample.

2.7 Fatty acids analysis

Fatty acids of soybean oil and optimal oils blend before and after thermal treatment were identified and quantified by Gas Chromatography according to ISO 5508 (ISO, 2003). In the preliminary step, fatty acid methyl esters (FAME) were prepared by methanolic boron triflouride (13–15%). Analysis was carried out by using a gas chromatograph (6890 Network GC System from Agilent Technologies, USA) equipped with a Flame Ionization Detector (FID) and split/splitless injector and fitted with a capillary column DB 23 Agilent 122-2362 (60 m × 0.25 mm internal diameter × 0.25 μm film thickness). The carrier gas was H_2 with a debit of one mL/min and a pressure of 14.84 psi. One microliter of the sample was injected in split mode with a ratio of 1:50. Initially, the oven temperature was maintained at 130 °C for one minute and afterward, increased to 170 °C at a rate of 6.5 °C/min, then from 170 to 215 °C at 2.75 °C/min and held at this temperature for 12 min; finally, it was quickly (40 °C/min) increased to 230 °C and held isotherm for 3 min. Injector and detector temperatures were set at 250 °C and 270 °C, respectively.

2.8 Statistical analysis

The results were expressed as the mean ± standard deviation of three replicates. The statistical analysis was performed using ANOVA following LSD test (Least Significant Difference) by Statistica Software version 10.0 (Stat Soft, Inc.). The data of simplex lattice mixture design were analyzed using JMP software version 10 (Statistical Analysis System Inc., SAS). The checking of qualities of mathematical models was evaluated by ANOVA and coefficients of regression by Student t-test.

3 Results and discussion

In order to better represent our research objectives regarding the improvement of refined soybean oil by blending with some cold-pressed oils, the results were divided into three parts. Part 1 attempts to provide the different physicochemical parameters, phenolic compounds, and antioxidant activity of studied oils (almond, nigella, lentisk, peanut, sesame, wild-olive, and soybean oils) for individual characterization. Part 2 focused on the binary blending effect of cold-pressed oils with soybean oil before and after thermal treatment. In the third part, the selected best three oils from the second investigation were combined through the simplex lattice mixture design for optimizing the oils blend. In addition, the fatty acid profiles obtained by GC-FID of the optimal oils blend before and after heating treatment were compared to soybean oil.

The physicochemical parameters allow describing the quality of oils and estimating their oxidation state. The UV absorption coefficient at specified wavelengths in the ultraviolet region is related to the formation of conjugated diene and products of primary oxidation (at 232 nm) and conjugated triene as well as products of secondary oxidation (at 270 nm). The higher absorption at 232 nm indicates the more peroxidized oil. Likewise, the absorption at 270 nm describes the increase of secondary oxidation products and reflects a low aptitude for preservation and thermal treatment of oil (Tanouti *et al.*, 2010; Kiritsakis and Markakis, 2012). The acidity (A_c) represents the percentage of free fatty acids conventionally expressed as oleic acid (Houmba *et al.*, 2016). The peroxide value (PV) represents the amount of active oxygen contained in a kilogram of the product (Novidzro *et al.*, 2019). The iodine value measured the unsaturation degree of fats and oils and hence their sensitivity to oxidation (Sudke and Sakarkar, 2013).

3.1 Cold-pressed oils characteristics

The results of physicochemical parameters, total phenolic compounds, and antioxidant activity were represented in Table 1. It can be noticed that soybean oil significantly presented the lowest values of oxidation indicators including UV absorption coefficients (K_{232} and K_{270}), acidity, and peroxide value which were within the recommended standards of refined soybean oil. This is evident because during the refining process, the physicochemical parameters (reduction of acidity, peroxide value, thiobarbituric acid, saponification value, and unsaponifiable matter) were ameliorated and the oxidative stability was improved but this technological process affected some bioactive compounds such as phenolic compounds (Onyema and Ibe, 2016; Mohdaly *et al.*, 2017). The results of some physicochemical parameters of the studied soybean oil including peroxide value (4.75 meq O_2/kg) and iodine value (117.01 g I_2/100 g) were in agreement with those found by Mohdaly *et al.* (2017). In contrast, mechanical extraction produces cold-pressed oils with lower quality physicochemical parameters while preserving their bioactive phytochemical compounds (Güneser *et al.*, 2017; Sakar *et al.*, 2021).

Among cold-pressed oils, almond, sesame, and lentisk oils were endowed globally with the best characteristics compared to wild-olive, nigella, and peanut oils. The rancimat test measures the resistance of oil to oxidation under a heated and oxygenated medium. The result of this test regarding lentisk oil stands out from others with an induction time of 26.83 h,

Table 1. Physicochemical parameters, total phenolic compounds, and RSA of analyzed studied oils.

Oils	K_{232}	K_{270}	Acidity	Peroxide value	Iodine value	Induction time	TPC	RSA
Almond	4.39 ± 0.18^{e}	3.59 ± 0.18^{c}	1.36 ± 0.04^{e}	6.00 ± 0.06^{d}	92.48 ± 0.92^{c}	13.12 ± 0.66^{d}	56.67 ± 1.70^{d}	34.57 ± 1.73^{d}
Lentisk	5.93 ± 0.12^{c}	5.66 ± 0.06^{a}	6.93 ± 0.14^{d}	4.40 ± 0.18^{e}	75.79 ± 3.79^{d}	26.83 ± 0.54^{a}	83.17 ± 2.53^{a}	46.29 ± 2.31^{b}
Nigella	11.27 ± 0.11^{b}	5.64 ± 0.23^{a}	8.26 ± 0.08^{b}	9.58 ± 0.29^{c}	81.47 ± 2.44^{d}	16.04 ± 0.48^{b}	63.16 ± 2.53^{b}	50.43 ± 1.01^{a}
Peanut	13.03 ± 0.39^{a}	5.78 ± 0.23^{a}	7.42 ± 0.15^{c}	15.56 ± 0.31^{a}	95.20 ± 0.95^{c}	9.00 ± 0.18^{e}	52.84 ± 0.53^{e}	15.43 ± 0.62^{g}
Sesame	5.47 ± 0.16^{d}	4.43 ± 0.18^{b}	1.38 ± 0.03^{e}	4.53 ± 0.18^{e}	106.08 ± 5.3^{b}	15.70 ± 0.16^{b}	60.71 ± 0.61^{bc}	37.43 ± 1.50^{c}
Wild-olive	5.68 ± 0.28^{cd}	4.45 ± 0.13^{b}	10.29 ± 0.31^{a}	11.17 ± 0.34^{b}	96.36 ± 4.82^{c}	8.87 ± 0.18^{e}	59.83 ± 1.20^{c}	26.71 ± 0.53^{f}
Soybean	3.17 ± 0.13^{f}	1.23 ± 0.01^{d}	0.23 ± 0.01^{f}	1.33 ± 0.07^{f}	124 ± 2.48^{a}	15.00 ± 0.15^{c}	42.36 ± 1.69^{f}	30.29 ± 0.30^{e}

K_{232} and K_{270}: UV absorption coefficients at 232 and 270 nm; Acidity, expressed as equivalent oleic acid percentage; Peroxide value, expressed as meq O_2/kg oil; Iodine value, expressed as mg KOH/g oil; Induction time (hour); TPC, expressed as mg GAE/100 g oil; RSA, $ABTS^+$ radical scavenging activity (%); for each column, results with different letters are statistically different (ANOVA-LSD, $p < 0.05$, a > b > c > d > e > f > g).

followed by nigella and sesame oils with similar values, and then soybean oil. However, peanut and wild-olive oils presented the weakest induction times. The results of total phenolic compounds indicated that lentisk and nigella oils were significantly the richest cold-pressed oils, which accordingly showed excellent antioxidant activities.

The data reported in the literature showed high variability in physicochemical parameters regarding cold-pressed oils. For example, the peroxide value of nigella oil reported by Kiralan *et al.* (2017) was 17.5 meq O_2/kg whereas Suri *et al.* (2019) found only 5.91 meq O_2/kg. Similarly, Kechidi *et al.* (2020) and Karoui *et al.* (2020), who studied lentisk oil, obtained respectively 6 and 1.92 meq O_2/kg for peroxide value and 14.41 and 4.14% for acidity. Genotype and several pre-harvest and post-harvest factors like cultivar, growing area, environmental condition, soil, harvest period, maturity, storage conditions, and oil extraction process can largely influence the physicochemical characteristics (Mele *et al.*, 2018; Salamatullah *et al.*, 2021; Ibourki *et al.*, 2022).

Indeed, it can be noted that despite the best physicochemical parameters of soybean oil, due to the refining process it has undergone, the phenolic content and antioxidant activity were significantly lower than those of cold-pressed oils. Thus, in order to improve the quality of refined soybean oil, each of the cold-pressed oils was mixed at a percentage of 30% with soybean oil (70%), and the different parameters of blends were analyzed before and after thermal treatment.

3.2 Binary blends of soybean oil with cold-pressed oils

Table 2 shows the results of physicochemical parameters of analyzed binary oil blends (30% of each oil with 70% of soybean oil) before and after thermal treatment as well as total phenolic compounds and antioxidant activity of untreated oils. In literature, variable ratios were used for oil blend formulations. It has been reported that soybean oil was added with 20% papaya oil, 20% melon oil, or with equal proportions of up to 40% for both in order to enhance the thermo-oxidation stability (Veronezi and Jorge, 2018). The same proportions and combinations were studied by Olagunju *et al.* (2022) using sesame and cashew nut oils. For improving the thermal stability of soybean oil, camellia seeds or tea seeds oils was added from 10 to 50% (Wang *et al.*, 2016) and from 20 to 50% (Prabsangob and Benjakul, 2018), respectively. To ameliorate the stability of oil during room storage, corn oil at different proportions (20, 40, 50, 60, and 80%) was blended with soybean oil (Thakkar and Parikh, 2014). In the present study, 30% of soybean oil were substituted by one or combined cold-pressed oils taking into account practical and economic aspects.

Before thermal treatment, the addition of cold-pressed oils to soybean oil produced a decrease in some physicochemical parameters (UV absorption coefficient, acidity, PV, and IV). This was due to the relatively low quality of these added cold-pressed oils. But the richness of these same cold-pressed oils in bioactive compounds significantly increased TPC and antioxidant activity of elaborated oil blends.

After thermal treatment, all quality characteristics of oil blends and soybean oil were significantly reduced but some of the cold-pressed oils manifested a considerable amelioration of the oxidative stability of soybean oil. It is clearly evident from the results that soybean oil mixed with lentisk oil has better parameters than control oil (soybean oil alone) with a significant reduction of both UV absorption coefficients (K_{232} and K_{270}) and acidity. Sesame oil was also an interesting substitute allowing a reduction of primary oxidation compounds that manifested by a low incidence on UV absorption coefficient at 270 nm and peroxide value compared to the control. The determination of peroxide value indicates the oxidation state of oils and reveals the level of oxidative rancidity of unsaturated fats. Oils with peroxide values less than 5 meq O_2/kg are considered to have an acceptable oxidation degree (Karoui *et al.*, 2020). Soybean oil blended with almond oil demonstrated a low acidity and peroxide value than soybean oil alone. The oil blends prepared with lentisk or sesame oils were characterized by high iodine value compared to soybean oil indicating a good protection of double-bounds. Whereas, soybean oil mixed with nigella, peanut or wild-olive oils presented equal or lower quality than control oil.

The improvement of quality parameters of soybean oil mixed with some cold-pressed oils can be explained by enrichment with phenolic compounds endowed with antioxidant activity allowing the enhancement of resistance to oxidation during heating treatment. For example, the use of lentisk oil in a binary system with soybean oil exhibited a

Table 2. Physicochemical parameters of analyzed binary oil blends (30% crude oil with 70% soybean oil) before and after thermal treatment.

Oils blend	Parameters before treatment							Parameters after treatment				
	K_{232}	K_{270}	Acidity	PV	IV	TPC	RSA	K_{232}	K_{270}	Acidity	PV	IV
Almond	3.51 ± 0.11^{d}	1.95 ± 0.06^{c}	0.56 ± 0.01^{e}	2.75 ± 0.11^{d}	114 ± 4.56^{bc}	44.6 ± 1.34^{d}	32.29 ± 0.97^{c}	38.56 ± 0.39^{bc}	6.29 ± 0.31^{b}	2.48 ± 0.02^{e}	4.37 ± 0.09^{e}	33 ± 0.99^{c}
Lentisk	3.98 ± 0.08^{c}	2.56 ± 0.10^{a}	2.26 ± 0.09^{d}	2.25 ± 0.02^{e}	110 ± 1.10^{c}	60.15 ± 0.60^{a}	40.43 ± 0.40^{a}	34.56 ± 1.73^{d}	4.92 ± 0.15^{c}	2.36 ± 0.07^{e}	6.35 ± 0.19^{b}	45 ± 2.25^{a}
Nigella	5.44 ± 0.27^{b}	2.57 ± 0.10^{a}	2.69 ± 0.13^{b}	3.75 ± 0.04^{c}	111 ± 2.22^{c}	53.36 ± 0.53^{b}	38.29 ± 0.77^{b}	41.36 ± 0.41^{a}	7.28 ± 0.29^{a}	4.06 ± 0.12^{a}	5.96 ± 0.12^{c}	30 ± 0.90^{d}
Peanut	6.09 ± 0.06^{a}	2.56 ± 0.10^{a}	2.41 ± 0.02^{c}	5.60 ± 0.11^{a}	114 ± 3.42^{bc}	49.98 ± 2.50^{c}	26.43 ± 1.06^{e}	42.64 ± 1.71^{a}	7.04 ± 0.28^{a}	3.57 ± 0.18^{c}	6.75 ± 0.07^{a}	33 ± 0.66^{c}
Sesame	3.86 ± 0.15^{c}	2.14 ± 0.09^{b}	0.56 ± 0.01^{e}	2.29 ± 0.02^{e}	118 ± 5.90^{ab}	49.01 ± 1.96^{c}	32.86 ± 0.33^{c}	39.04 ± 1.56^{bc}	5.28 ± 0.05^{c}	3.47 ± 0.14^{c}	4.96 ± 0.15^{d}	46 ± 1.84^{a}
Wild-olive	3.89 ± 0.16^{c}	2.17 ± 0.09^{b}	3.10 ± 0.09^{a}	4.25 ± 0.13^{b}	116 ± 2.32^{bc}	55.2 ± 1.66^{b}	29.86 ± 1.49^{d}	38.46 ± 0.77^{c}	6.63 ± 0.20^{b}	3.83 ± 0.08^{b}	5.75 ± 0.17^{c}	31 ± 0.93^{cd}
Control (Soybean oil)	3.17 ± 0.13^{e}	1.23 ± 0.06^{d}	0.23 ± 0.01^{f}	1.33 ± 0.03^{f}	124 ± 4.96^{a}	42.36 ± 0.85^{d}	30.29 ± 0.30^{d}	40.62 ± 0.81^{ab}	6.47 ± 0.19^{b}	3.26 ± 0.10^{d}	6.5 ± 0.33^{ab}	40 ± 1.60^{b}

K_{232} and K_{270}: UV absorption coefficients at 232 and 270 nm; Acidity, expressed as equivalent oleic acid percentage; Peroxide value (PV), expressed as milliequivalents oxygen/kg oil; Iodine value (IV), expressed as mg KOH/g oil; TPC, expressed as mg GAE/100 g oil; RSA, $ABTS^{+}$ radical scavenging activity (%); for each column, results with different letters are statistically different (ANOVA-LSD, $p < 0.05$, a > b > c > d > e > f).

Table 3. Physicochemical and antioxidant parameters of simplex lattice design of oil blends before thermal treatment.

Run	Variables			Parameters before treatment						
	Lentisk oil (x_1)	Almond oil (x_2)	Sesame oil (x_3)	K_{232}	K_{270}	Acidity	PV	IV	TPC	RSA
1	1	0	0	4.07	2.47	2.25	2.23	106.70	70.45	40.03
2	0.67	0.33	0	3.94	2.34	1.78	2.47	113.99	55.07	37.21
3	0.33	0.67	0	3.70	2.24	1.16	2.54	110.22	49.58	35.20
4	0	1	0	3.52	2.03	0.53	2.86	115.36	45.00	32.19
5	0	0.33	0.67	3.66	2.16	0.56	2.45	112.86	47.64	32.37
6	0.33	0.33	0.33	3.71	2.32	1.13	2.40	114.58	51.65	35.69
7	0.33	0	0.67	3.91	2.42	1.17	2.34	109.93	52.42	35.38
8	0.67	0	0.33	4.11	2.40	1.72	2.24	113.90	55.94	38.40
9	0	0	1	3.68	2.23	0.54	2.41	119.60	49.51	32.76
10	0	0.67	0.33	3.51	2.19	0.53	2.59	116.39	45.57	32.28

x_1: lentisk oil; x_2: almond oil; x_3: sesame oil; K_{232} and K_{270}: UV absorption coefficients at 232 and 270 nm; Acidity, expressed as percentage equivalent of linoleic acid; Peroxide value (PV), expressed as meq O_2/kg oil; Iodine value (IV), expressed as mg KOH/g oil; TPC, expressed as mg GAE/100 g oil; RSA, $ABTS^+$ radical scavenging activity (%).

significant increase in TPC and antioxidant activity with 42 and 33%, respectively. This would undoubtedly be due to the high TPC amounts of lentisk cold-pressed oil (83.17 mg GAE/100 g) which manifested an antioxidant activity higher than that of soybean oil. According to the study of Karoui *et al.* (2020), the oil of *Pistacia lentiscus* seeds seemed to be a good source of antioxidant agents (phytosterols and tocopherols).

Blending oils at certain proportions provide new products with better functional properties and specific uses. Many studies demonstrated that mixing some vegetable oils allows a change in fatty acid profiles and gives higher contents of natural bioactive compounds, therefore, can enhance the stability of oils and improve their nutritional value (Hashempour-Baltork *et al.*, 2016). Numerous works demonstrated that physicochemical, nutritional, and antioxidant characteristics of soybean oil were improved by blending with unrefined oils. Vidrih *et al.* (2010) found that unrefined oils have better and longer oxidative stability and are more suitable for frying than refined oils. Indeed, the quality of soybean oil, measured by stability index and peroxide value, blended with sesame oil (60:40) has been strongly ameliorated. This is related to the presence of antioxidants (sesamol, sesamol dimer, sesamolin, and tocopherols) in sesame oil that improved the thermo-oxidative stability of soybean oil (Chu and Kung, 1998). Furthermore, Hashempour-Baltork *et al.* (2016) showed that the peroxide value and radical scavenging activity of flaxseed oil were significantly improved by the addition of sesame or peanut oils. Hamed and Abo-Elwafa (2012) observed that the blending of flaxseed oil (containing a high content of polyunsaturated fatty acids) with other oils rich in natural antioxidants, like *Nigella sativa* seeds oil, solved the problem and limits the oxidation. The oils blend formed by mixing sea buckthorn, camellia, rice bran, sesame, or peanut oils with soybean oil (at a level of 20%) demonstrated an interesting improvement in oxidative stability compared to soybean oil alone (Li *et al.*, 2014). The authors suggested that these added oils could contribute as important sources of natural antioxidants. The effectiveness of antioxidants in protecting oils from oxidation is well studied and established (Ahn *et al.*, 2012; Zhao *et al.*, 2017; Umeda and Jorge, 2021).

According to the statistical analysis of the results of binary oil blends obtained in this study, it can be retained that lentisk oil, followed by sesame oil and then almond oil improved the physicochemical parameters and antioxidant properties of soybean oil after thermal treatment. These three oils were selected and combined following the simplex lattice mixture design in order to find the best oils proportion that maximizes the oxidative stability of soybean oil.

3.3 Simplex lattice mixture design

The simplex lattice mixture design was applied for searching the best combination among the three selected oils that maximize the thermo-resistance of soybean oil. This method operates by planning a series of experiments with good distribution in the studied space. The mixture designs have demonstrated their effectiveness in the evaluation of component effects on the targeted responses of the mixtures (Benbouriche *et al.*, 2021; Yuksel *et al.*, 2022).

The results of the physicochemical parameters, TPC, and antioxidant activity of different oil combinations of the simplex lattice design before thermal treatment were represented in Table 3. Overall, it can be noticed from this table that the analyzed parameters of the different mixed oils varied proportionally with percentages of added cold-pressed oils.

The results of physicochemical parameters obtained experimentally and calculated through mixture design after thermal treatment were given in Table 4. All quality characteristics of heat-treated oils were significantly reduced compared to untreated oils, which appears evident due to the heating process that induces the oxidation of oils. It can be observed from the results of heat-treated oils that the combination of both lentisk and sesame oils with soybean oil improved considerably all analyzed parameters (runs 7 and 8), but the introduction of almond oil reduced significantly the

Table 4. Physicochemical parameters of simplex lattice design of oils after thermal treatment and corresponding predicted values.

Run	Variables			Experimental						Predicted					
	Lentisk oil (x_1)	Almond oil (x_2)	Sesame oil (x_3)	K_{232}	K_{270}	Acidity	PV	IV	IT	K_{232}	K_{270}	Acidity	PV	IV	IT
1	1	0	0	34.94	5.00	2.37	4.00	43.00	17.94	35.30	5.25	2.49	4.03	41.77	18.09
2	0.67	0.33	0	36.12	7.08	2.96	4.50	39.60	17.14	36.02	6.74	2.89	4.46	42.01	16.54
3	0.33	0.67	0	38.62	7.28	3.11	5.10	43.80	14.92	37.95	7.40	3.03	5.24	39.26	15.25
4	0	1	0	39.62	7.06	2.81	6.50	32.30	14.28	41.09	7.23	2.92	6.37	33.52	14.21
5	0	0.33	0.67	33.70	4.72	3.26	5.05	50.80	15.03	36.65	5.14	3.37	4.89	47.77	14.88
6	0.33	0.33	0.33	29.06	4.78	2.22	5.00	62.80	14.76	30.62	5.22	2.53	4.81	67.07	15.30
7	0.33	0	0.67	24.36	3.54	1.92	4.50	91.80	16.40	24.55	3.71	2.05	4.63	88.39	15.98
8	0.67	0	0.33	25.18	4.16	1.95	4.50	86.00	16.47	24.21	3.76	1.67	4.47	87.27	16.62
9	0	0	1	37.38	5.30	3.70	4.51	43.00	15.95	36.33	5.10	3.62	4.52	45.15	16.14
10	0	0.67	0.33	41.96	6.50	3.40	5.25	43.00	14.35	38.23	5.85	3.14	5.51	43.89	14.23

x_1: lentisk oil; x_2: almond oil; x_3: sesame oil; K_{232} and K_{270}: UV absorption coefficients at 232 and 270 nm; Acidity, expressed as percentage equivalent of linoleic acid; Peroxide value (PV), expressed as meq O_2/kg oil; Iodine value (IV), expressed as mg KOH/g oil; Induction time (IT), expressed in hours.

Table 5. Adjustment and variance analysis of models.

Variable	Source	DF	Coefficient of determination	Sum of squares	*F* ratio
K_{232}	Model	5	$R^2 = 0.909$	298.396	8.004
	Residues	4	Adj. $R^2 = 0.796$	29.824	Prob. > F
	Total model	9		328.220	0.0329*
K_{270}	Model	5	$R^2 = 0.910$	3.196	9.587
	Residues	4	Adj. $R^2 = 0.797$	0.317	Prob. > F
	Total model	9		3.513	0.0324*
Acidity	Model	5	$R^2 = 0.909$	0.091	7.9439
	Residues	4	Adj. $R^2 = 0.794$	0.009	Prob. > F
	Total model	9		0.100	0.0333*
Peroxide value	Model	5	$R^2 = 0.925$	3.859	9.897
	Residues	4	Adj. $R^2 = 0.832$	0.312	Prob. > F
	Total model	9		4.171	0.0227*
Iodine value	Model	5	$R^2 = 0.980$	3608.781	38.235
	Residues	4	Adj. $R^2 = 0.954$	75.508	Prob. > F
	Total model	9		3684.289	0.0018*
Induction time	Model	5	$R^2 = 0.924$	12.946	9.730
	Residues	4	Adj. $R^2 = 0.829$	1.064	Prob. > F
	Total model	9		14.011	0.0234*

characteristics of the blend. The experimental and calculated results of the analyzed parameters were very close (Tab. 4) which is supported by the coefficient of determination (R^2) that varied from 0.909 to 0.980 (Tab. 5). R^2 indicates the amount of total variability explained by the regression model that measures the linear association between experimental and predicted values of the response. This statistical parameter is included between −1 and +1, which is used for checking the goodness of the model (Bachir bey *et al.*, 2014; Bonicelli *et al.*, 2015). The analysis of the variance of the models was presented in Table 5. Fisher probability values of models obtained for all studied parameters were less than 0.05, indicating that elaborated models were significant and presented a high power of experimental prediction.

The use of mixture design for vegetable oils combination was previously used for different objectives. For example, the blending of safflower, linseed, and soybean oils in order to optimize frying oil composition with higher essential fatty acids was studied by Meinhart *et al.* (2017). An experimental mixture design was also used to ameliorate the sensory quality of extra virgin olive oils provided from four cultivars (Vojnovic *et al.*, 1995). Studies that have used this statistical approach have found satisfaction and good usefulness to reach their purposes. As all analyzed parameters in this work presented a good mathematical adjustment and high significance of models, checking details on each factor was necessary.

3.4 Effect of factors

The effects of the addition of lentisk, almond, and sesame oils on the thermo-resistance of soybean oil and their interactions on the response after thermal treatment were shown in Table 6. The three factors significantly influenced all analyzed parameters ($p < 0.05$). The interaction of lentisk and sesame oils in the formulation of oils blend was statistically significant, which expressed a negative influence for K_{232}, K_{270}, acidity, and peroxide value and positive for iodine value. This indicated that the simultaneous increase of both lentisk and sesame oils in oil blends induced a reduction in the incidence of oxidation and degradation with an increase in the protection of double bonds.

The mathematical models of analyzed parameters obtained from the mixture design of oil blends can be presented as first-order polynomials. The mathematical models taking into account the linear and interaction effects of responses and considering the terms with significant influences can be presented as following equations (7) to (12);

$$Y_{K232} = 35.30x_1 + 41.09x_2 + 36.33x_3 - 51.45x_1x_3, \quad (7)$$

$$Y_{K720} = 5.25x_1 + 7.23x_2 + 5.10x_3 - 6.45x_1x_3, \quad (8)$$

$$Y_{Acidity} = 2.49x_1 + 2.92x_2 + 3.62x_3 - 5.39x_1x_3, \quad (9)$$

$$Y_{PV} = 6.57x_1 + 4.53x_2 + 5.08x_3 - 4.02x_1x_3 - 4.69x_1x_3, \quad (10)$$

$$Y_{IV} = 41.77x_1 + 33.52x_2 + 45.15x_3 + 199.67x_1x_3, \quad (11)$$

$$Y_{IT} = 18.09x_1 + 14.21x_2 + 16.14x_3, \quad (12)$$

where Y is the response; x_1 is the lentisk oil; x_2 is the almond oil; x_3 is the sesame oil; PV is the peroxide value; IV is the iodine value; IT is the induction time.

Many studies demonstrated that blending oils with different compositions can produce mixtures with ameliorated properties. Admixing virgin olive oil with other less stable edible oils (sunflower and soybean oils) at a level of 20 or 40% leads to enhancement of physicochemical parameters (peroxide value, free fatty acids, iodine value, and fatty acid composition) and oxidative stability. This was related to the oxidation resistance of virgin olive oil because of its high contents of natural antioxidants and lower unsaturation fatty acid levels (Abdel-Razek *et al.*, 2011). Other oils were also used to ameliorate the performance of soybean oil such as sesame, camellia, rice bran, sea buckthorn, and peanut oils (Li *et al.*, 2014). The application of mixture design for frying oil formulation, based on four vegetable oils, revealed that increasing contributions of sunflower and corn oils in blends resulted in the increase of oxidative stability but the increasing proportions of canola and sesame oils affected negatively the thermo-stability (Raftani Amiri *et al.*, 2019).

3.5 Experimental determination and validation of optimal combination

The different responses of oil blends can be illustrated by isoresponse plot (Fig. 1). In order to predict the optimal desirability taking into account the combined parameters, the profiler of prediction of JMP was used. The estimated optimal combination of the three oils was 59% lentisk oil and 41% sesame oil without adding almond oil. Hence, the thermo-oxidative stability of soybean oil can be enhanced by blending 70% of soybean oil with 17.7 and 12.3% of lentisk and sesame oils, respectively. The predicted values of different physicochemical parameters were indicated in Table 7. To confirm the optimal theoretical values, an experimental validation was carried out. For this, the optimal mixture of oils blend was tested. The experimental result (Tab. 7) of each obtained parameter was very close to theoretical values and the Student t-test did not reveal any difference between actual and calculated values of studied variables (physicochemical traits) indicating the validity of the established mathematical models.

3.6 Effect of heat treatment on fatty acids composition of soybean oil *vs.* optimal oils blend

Gas chromatography analysis of FAME derivatives revealed the presence of fifteen fatty acids in both soybean oil and optimal oils blend (70% soybean oil: 17.7% lentisk oil: 12.3% sesame oil). The results showed that blending soybean oil with lentisk and sesame oils changed slightly the fatty acids composition. However, the obtained oils blend presented a significantly ($p < 0.05$) high fraction of oleic acid and less level of linoleic acid than soybean oil alone (Tab. 8). The presence of polyunsaturated fatty acids (PUFA) at low levels (50.21%) and high level of monounsaturated (MUFA, 31.89%) in oils blend compared to soybean oil (57.12% PUFA and 26.07% MUFA) may explain its implication on thermal stability that was supported by the results of rancimat test. It was demonstrated that oils rich in MUFA have greater thermal stability than those containing high PUFA (Ramadan, 2013). Thus, lentisk and sesame oils were considered good nutritive quality because of their higher unsaturated fatty acids content, especially MUFA (52.8 and 41.8% respectively), and lower PUFA content (23.5 and 39.2% respectively) than soybean oil (Ghosh *et al.*, 2019; Ait Mohand *et al.*, 2020). Furthermore, the results in Table 8 showed another factor involved in the thermal stability of the oils blend. It was noted that the level of the degradation of linoleic (ω6) and linolenic acids (ω3) was more important in soybean oil than in blended oil; 31% of linoleic acid was degraded after heat treatment of soybean oil, but only 6.5% was lost in blended oil. Likewise, the level of thermal degradation of linolenic acid was 94% in soybean oil and only 45% in blended oil. The ratio ω6/ω3 after heat-treatment was very low in oils blend (18.87) compared to soybean oil (118.18). It was established that a high ω6/ω3 ratio consumption promotes the pathogenesis of many diseases, including cardiovascular disorder, cancer, inflammatory, and

Table 6. Coefficients of mathematical equations of models and their statistical significance.

Term	K_{232}		K_{270}		Acidity		Peroxide value		Iodine value		Induction time	
	Estimation	Prob.>|t|	Estimation	Prob.>|t|	Estimation	Prob.>|t|	Estimation	Prob.>|t|	Estimation	Prob.>|t|	Estimation	Prob.>|t|
Lentisk oil	35.30	0.0002*	5.25	0.0006*	2.49	0.0007*	6.57	< 0.0001*	41.77	0.0005*	18.09	< 0.0001*
Almond oil	41.09	< 0.0001*	7.23	0.0002*	2.92	0.0004*	4.53	< 0.0001*	33.52	0.0012*	14.21	< 0.0001*
Sesame oil	36.33	0.0001*	5.10	0.0006*	3.62	0.0002*	5.08	< 0.0001*	45.15	0.0004*	16.14	< 0.0001*
Lentisk oil*Almond oil	−5.45	0.6568	3.73	0.1836	1.13	0.3891	−4.02	0.026*	13.44	0.4992	−1.14	0.6226
Lentisk oil*Sesame oil	−51.45	0.0106*	−6.45	0.0498*	−5.39	0.0101*	−4.69	0.0157*	199.67	0.0004*	−3.67	0.1628
Almond oil*Sesame oil	−5.71	0.6422	−3.01	0.2648	−0.09	0.9425	−0.55	0.6631	29.25	0.1814	−2.80	0.2631

K_{232} and K_{270}: UV absorption coefficients at 232 and 270 nm; Acidity, expressed as equivalent oleic acid percentage; Peroxide value (PV), expressed as milliequivalents oxygen/kg oil; Iodine value (IV), expressed as mg KOH/g oil; Induction time (hour); * indicates a significant value.

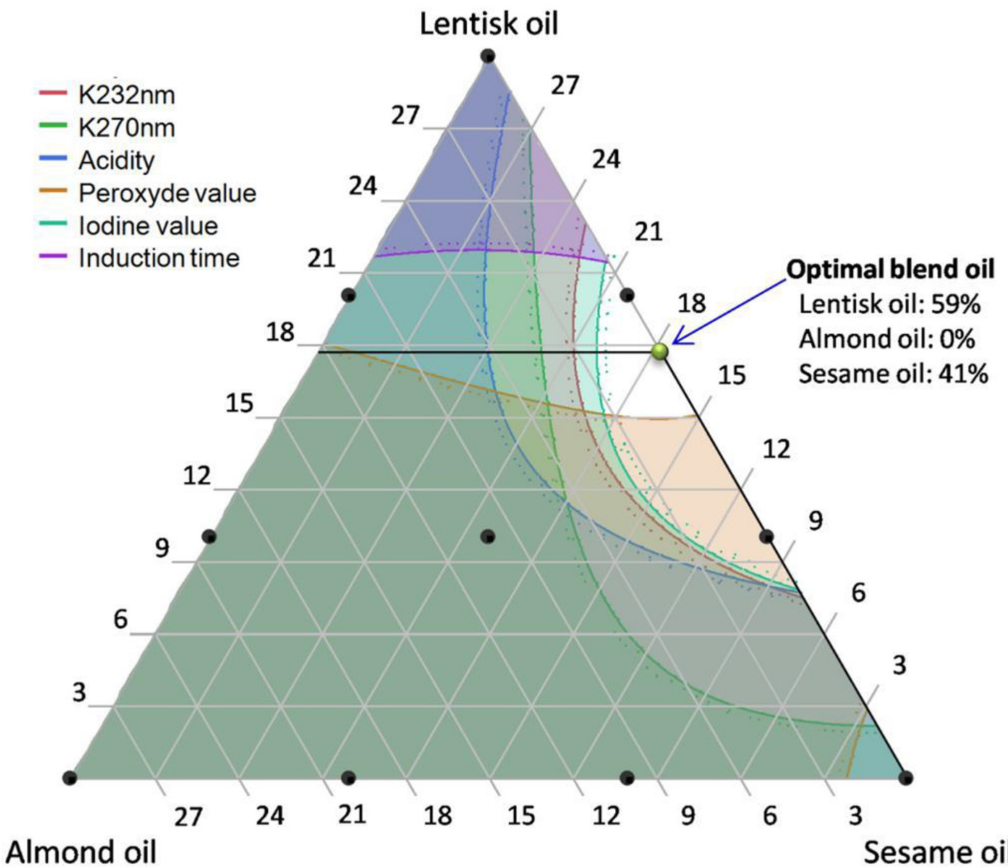

Fig. 1. Ternary contour plots representing the effects of oils blended (lentisk, almond, and sesame oils) on physicochemical parameters (K_{232}, K_{270}, acidity, and peroxide and iodine values) after thermal treatment.

Table 7. Optimal values of predicted and experimental parameters.

Parameters	Optimal	
	Predicted	Experimental
Lentisk oil (%)	17.7	/
Sesame oil (%)	12.3	/
Almond oil (%)	0	/
K_{232}	23.24	25.12 ± 2.45
K_{270}	3.52	4.22 ± 0.38
Acidity	1.65	1.73 ± 0.08
Peroxide value	4.53	4.48 ± 0.13
Iodine value	91.64	86.64 ± 3.95
Induction time	16.39	17.36 ± 1.18

K_{232} and K_{270}: UV absorption coefficients at 232 and 270 nm; Acidity, expressed as equivalent oleic acid percentage; Peroxide value (PV), expressed as milliequivalents oxygen/kg oil; Iodine value (IV), expressed as mg KOH/g oil; Induction time (hour).

autoimmune diseases due to the excess of linoleic acid (ω6) (Simopoulos, 2002). The rich antioxidant substances in lentisk and sesame oils seem to protect both linoleic and linolenic acids from thermal degradation.

4 Conclusion

Refined soybean oil was chosen in this study in order to improve its thermo-resistance. This oil demonstrated good initial physicochemical characteristics but presented relatively low antioxidant properties. The binary blending of this oil with some cold pressed oils, characterized by high levels of phenolic compounds and antioxidant activities, revealed a significant amelioration of thermo-stability, particularly using lentisk, sesame, or almond oil. The application of mixture design on the last three oils with soybean oil (70%) gives an optimal combination of 17.7% lentisk oil and 12.3% sesame oil without almond oil. Thermo-stability of the optimal oils blend was demonstrated through considerable improvement of physicochemical characteristics, antioxidant properties, and fatty acids profile especially linoleic acid (ω6) and linolenic acid (ω3) (essentials fatty acids) and their ratio. The addition of these two cold-pressed oils to refined soybean oil had two consequences; the decrease in the fraction of polyunsaturated fatty acids, which are very susceptible to oxidation, and the increase in antioxidants level.

Declaration of conflict of interest

The authors declare that they have no conflict of interest regarding the present work.

Table 8. Fatty acids composition (%).

Fatty acid	Chemical structure	Retention time (min)	Soybean oil (%)	Soybean oil after heating treatment (%)	Blended soybean oil (%)	Blended soybean oil after heating treatment (%)
Myristic acid	CI4:0	12.086	0.080 ± 0.001^{b}	0.118 ± 0.013^{a}	0.070 ± 0.001^{c}	0.072 ± 0.009^{c}
Palmitic acid	C16:0	14.175	10.770 ± 0.038^{b}	13.008 ± 1.581^{a}	12.619 ± 1.220^{a}	13.074 ± 1.120^{a}
Palmitoleic acid	C16:1	14.434	0.097 ± 0.011^{d}	0.112 ± 0.003^{c}	0.348 ± 0.023^{a}	0.353 ± 0.005^{a}
Margaric acid	C17:0	14.949	0.093 ± 0.001^{b}	0.134 ± 0.018^{a}	0.083 ± 0.001^{c}	0.087 ± 0.003^{c}
Margaroleic acid	C17:1	15.282	0.054 ± 0.001^{b}	0.077 ± 0.001^{a}	0.053 ± 0.002^{b}	0.054 ± 0.001^{b}
Stearic acid	C18:0	16.640	3.489 ± 0.122^{b}	4.921 ± 0.712^{a}	3.563 ± 0.289^{b}	3.692 ± 0.265^{b}
Oleic acid	C18:1*cis* ω9	17.061	24.198 ± 0.656^{b}	29.089 ± 0.895^{a}	29.927 ± 0.156^{a}	30.526 ± 0.235^{a}
Oleic acid	C18:1*cis* ω7	17.116	1.482 ± 0.048^{b}	1.849 ± 0.058^{a}	1.338 ± 0.035^{c}	1.373 ± 0.054^{c}
Linoleic acid	C18:2 ω6	17.851	51.531 ± 0.581^{a}	35.603 ± 0.848^{d}	45.971 ± 0.247^{b}	43.205 ± 0.563^{c}
Linolenic acid	C18:3 ω3	18.555	5.585 ± 0.185^{a}	0.302 ± 0.093^{d}	4.173 ± 0.089^{b}	2.291 ± 0.029^{c}
Arachidic acid	C20:0	19.184	0.380 ± 0.010^{c}	0.735 ± 0.104^{a}	0.391 ± 0.012^{c}	0.511 ± 0.096^{b}
Gadoleic acid	C20:1	19.617	0.234 ± 0.004^{c}	0.529 ± 0.001^{a}	0.220 ± 0.006^{c}	0.269 ± 0.001^{b}
Dihomolinoleic acid	C20:2	21.146	0.076 ± 0.000^{a}	0.072 ± 0.009^{b}	0.063 ± 0.001^{c}	0.066 ± 0.003^{c}
Behenic acid	C22:0	22.146	0.491 ± 0.003^{b}	0.542 ± 0.107^{a}	0.384 ± 0.005^{d}	0.451 ± 0.004^{c}
Lignoceric acid	C24:0	26.123	0.173 ± 0.020^{c}	0.289 ± 0.014^{a}	0.148 ± 0.082^{d}	0.182 ± 0.017^{b}
Total SFA			15.476	19.747	17.258	18.069
Total MUFA			26.065	31.656	31.886	32.575
Total PUFA			57.116	35.977	50.207	45.496

SFA: saturated fatty acids; MUFA: monounsaturated fatty acids; PUFA: polyunsaturated fatty acids; for each row, results with different letters are statistically different (ANOVA-LSD, $p < 0.05$, a > b > c > d).

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