Journal of Oleo Science
Copyright ©2023 by Japan Oil Chemists' Society
doi : 10.5650/jos.ess23016
J. Oleo Sci. **72**, *(10) 901-910 (2023)*

Improvement in Frying Stability of Safflower Oil by Blending with Refined Olive Pomace Oil during Deep Fat Frying

Ezgi Genç Yılmaz[1]* and Aslı Yorulmaz[2]

[1] *İstanbul Gelişim University, Vocational School of Health Services, Department of Food Quality Control and Analysis, Istanbul, TURKEY*
[2] *Aydın Adnan Menderes University, Faculty of Engineering, Department of Food Engineering, Aydın, TURKEY*

Abstract: The objective of the present study was to increase the frying stability of refined safflower oil (RSO) by blending it with refined olive pomace oil (ROPO) during deep fat frying. For this purpose; RSO, ROPO and their blends were utilized for frying of potato sticks at 180°C for 3 consecutive days. The frying stability of the oils was monitored by analyzing them for their free fatty acids, peroxide values, total polar contents, ultraviolet spectrophotometric indices at 232 and 270 nm, fatty acid profiles, *p*-anisidine values, α-tocopherol contents and photometric color indices. 3-monochloropropane-1,2-diol (3-MCPD) and glycidyl ester (GE) levels of oils before and after frying were measured as well. The results have shown that thermo-oxidative degradation products increased as the frying progressed for all oils, however the decomposition rate was found to slow down in blend oils by stabilizing with ROPO. Blending RSO with ROPO decreased linoleic and linolenic; but increased the oleic and palmitic acid percentages of the blends. C18:2/C16:0 ratio was found to decrease by frying for RSO and the blend oils, however ROPO was not affected significantly. 3-MCPD-E levels of the blends increased as the ratio of ROPO increased. Principal component analysis enabled a clear discrimination between oils with different composition throughout the frying process.

Key words: blending, fatty acid composition, frying stability, olive pomace oil, safflower oil

1 Introduction

Deep fat frying is a process of dehydration and cooking through the complete contact of the food surface with hot oil at 150-200℃. The resultant fried products are highly preferred by the consumers due to their palatable taste, low cost as well as the rapid and easy preparation techniques. During frying, common chemical reactions, namely, hydrolysis, oxidation and polymerization occur and generate volatile and non-volatile compounds which alter the chemical and nutritional properties of the oil and the fried product. There are many parameters affecting the rate of these degradation reactions such as the quality of the oil, the properties of the food, food/oil ratio, frying temperature and time, design of fryer etc. Among all these factors, the type of the frying oil has critical importance since it is absorbed by the food and elicits the breakdown compounds which can affect human health adversely[1]. Therefore, the preference of the frying oils with high stability is a relevant aspect to achieve a good quality fried product.

Vegetable oils are distinguished by their characteristic stabilities against oxidation depending on their fatty acid profile and antioxidant content. The oils containing high levels of polyunsaturated fatty acids are known to be more prone to oxidation and thermal degradation[2]. Hence, the oils rich in monounsaturated fatty acids (e.g. oleic acid) with low amounts of polyunsaturated fatty acids (e.g. linoleic and linolenic acids) are favoured owing to their higher stabilities[3]. Modifying the fatty acid profile through different techniques such as fractionation, interesterification, hydrogenation or their combination is a common strategy of improving the stabilities of the oils. Blending has been regarded as a more economical and simpler way of enhancing the stability, chemical and nutritional characteristics of vegetable oils. The properties of oil blends can be adjusted as to meet the requirements of deep fat frying applications in the food industry.

Safflower oil is derived from the seeds of safflower (*Carthamus tinctorius* L.), which is mainly grown in Asia, North America and South America[4]. The oil contains high proportions of essential fatty acids, particularly linoleic

*Correspondence to: Ezgi Genç Yılmaz, İstanbul Gelişim University, Vocational School of Health Services, Department of Food Quality Control and Analysis, Istanbul, TURKEY
E-mail: egenc@gelisim.edu.tr ORCID ID: https://orcid.org/0000-0002-9772-6283
Accepted July 14, 2023 (received for review February 1, 2023)
Journal of Oleo Science ISSN 1345-8957 print / ISSN 1347-3352 online
http://www.jstage.jst.go.jp/browse/jos/ http://mc.manusriptcentral.com/jjocs

acid (77.9-79.5%)[5]. The oil also represents a rich source of natural antioxidants especially of α-tocopherol (46.05–70.93 mg/100 g)[6]. The conjugated linoleic acid in safflower oil has been reported to reduce body weight and adipose tissues as displayed in clinical trials[7]. Moreover, safflower oil has been determined to be effective in fat-induced insulin resistance[8]. Safflower oil shows similarity to sunflower oil in terms of its color and flavor[9]. However, high content of polyunsaturated fatty acid (PUFA) makes safflower oil vulnerable to undesired thermal degradation and limits its utilization as frying oil.

Olive oil is known for its strong oxidative stability due to its high monounsaturated fatty acid and minor antioxidant compound content. Olive pomace is the by-product of olive oil production process and contains notable amount of oil which can be up to 8% depending on the extraction technique[10]. Nowadays, the evaluation and reduction of by-products is one of the most important efforts of the food industry for a sustainable food production chain. The residual oil in the olive pomace is recovered by treating the dry cake by solvent extraction and the obtained crude olive pomace oil is refined before further consumption. Olive pomace oil has similar chemical composition with olive oil and its fatty acid profile is mainly composed of oleic acid covering up to the 85% of the total fatty acids. The oil also contains a wide variety of minor components, such as triterpenic acids and dialcohols, squalene, tocopherols, sterols, aliphatic fatty alcohols and phenolic compounds that may contribute to its health-promoting attributes[11]. Olive-extracted oils have been reported to be resistant to thermo-oxidation and are preferable for frying purposes owing to their high monounsaturated to polyunsaturated fatty acid ratio as well as the presence of minor components with protective effects[12]. Although, the refining process that crude olive pomace oil undergoes for further consumption reduces some bioactives, the minor components still remain at concentrations that can induce health benefits, specially on cardiovascular health[13]. Moreover, olive pomace oil is quite economical when compared to olive oil. Therefore, olive pomace oil has great potential for oil blend applications with less stable vegetable oils to improve frying oil stabilities.

Based on above considerations, the current research was conducted to prepare RSO and ROPO blends for a balanced fatty acid profile and to develop a healthier deep-fat frying medium. The frying oil blends available in the literature are generally based on the mix of oils rich in saturated and polyunsaturated fatty acids. Instead, to increase the frying stability of PUFA rich oils, blending with monounsaturated fatty acid (MUFA) rich ones will also minimize the health problems caused by the presence of saturated fatty acids with high melting points. Moreover, the study aims to open a new area for the utilization of olive pomace oil, which is still an underused by-product with positive health benefits. The purpose of the study was to monitor the frying performance of RSO since little has been published on the topic and to assess the acceptance of safflower oil as frying oil by blending with olive pomace oil. To the best of authors' knowledge, the effect of partial replacement of safflower oil with olive pomace oil for the purpose of improving the frying stability has not been reported so far. The comparative study of frying behaviors of different oil blends has critical importance to explore the most suitable oil mix for deep frying processes. Thus, RSO, ROPO and their blends (80:20 and 50:50 v/v) were used to fry potato sticks at 180℃ for three consecutive days. The free acidity, total polar content, color index, peroxide value, *p*-anisidine value, spectrophotometric indices, α-tocopherol contents and fatty acid compositions of oils throughout frying were monitored. In addition, changes in the levels of 3-MCPD and GEs of RSO, ROPO and their blends by the frying process were investigated for the first time.

2 Materials and Methods

2.1 Material

RSO was kindly supplied by Reka Edible Oil Industry and Trade Inc. (Tekirdağ, Turkey) and ROPO was kindly provided by Orpir-Doğuş Pirina Factories (Balıkesir, Turkey). Two oil blends were prepared by blending refined safflower oil with refined olive pomace oil: (1) RSO (80):ROPO (20), v/v, (2) RSO (50):ROPO (50), v/v. The oils were mixed homogeneously and subjected to frying treatments. Pure RSO and ROPO were also used for frying applications. The frozen pre-fried potato sticks (SuperFresh Kerevitaş Gıda San. ve Tic. A.Ş., Turkey) were purchased from a local supermarket.

2.2 Reagents and standards

Diethyl ether, ethanol, phenolphthalein, sodium hydroxide, isooctane, methanol, potassium hydroxide, hydrochloric acid, *n*-hexane, isopropanol, toluene, sodium chloride, sodium bromide, tert-butyl methyl ether, ethyl acetate and sodium sulfate were obtained from Merck (Darmstadt, Germany). Sodium methoxide, sodium hydroxide, sulfuric acid, *p*-anisidine, methyl orange, α-tocopherol standard, 3-chloro-1,2-propanediol, 3-chloro-1,2-propanediol-d5, glycidol were purchased from Sigma-Aldrich (St-Louis, USA) and 37 fatty acid methyl ester mix was from Supelco (Bellefonte, USA).

2.3 Frying procedure

The frying trials were carried out with an electrical, stainless steel, industrial fryer (Remte, Turkey). For each process, 75 grams of french fries were fried in 2 L of oil at 180℃ for 3 minutes. French fries were removed from the frying oil at the end of the 3-minute frying period. Frying

was conducted in 1 hour cycles for 8 hours daily for 3 consecutive days. The total frying time was 24 hours. The frying oil was not changed during the process and the fryers were left uncovered during the experiment. The temperature was continuously measured with a temperature measuring device (Testo176 T4). At the end of the day, the fryers were turned off and the oil was cooled to ambient temperature, filtered and stored at 4℃ until the following day. The oil was topped to initial level each day to replenish the used oil before the frying process. Oil samples of 100 mL were taken from the 4th and 8th frying cycles daily and kept in dark glass bottles at 4℃ until analysis.

2.4 Analysis

2.4.1 Free fatty acidity

The free fatty acidity was determined according to AOCS Official Method Ca 5a-40[14] and expressed as the percentage of oleic acid.

2.4.2 Peroxide value

Peroxide value (PV) of the samples were determined according to AOCS Official Method Cd 8-53[14].

2.4.3 UV spectrophotometric indices (K_{232}, K_{270})

K_{232} and K_{270} values were determined according to AOCS Official Method Ch 5-91[14].

2.4.4 *p*-Anisidine value

The *p*-anisidine value of the frying oils were determined using the AOCS Cd 18–90 Official Method[14].

2.4.5 Total polar compounds

Total polar compounds were measured using an electrochemical sensor (Testo 270, Testo AG, Lenzkirch, Germany). The total polar compound values were measured during frying by immersing the probe into the hot oil.

2.4.6 Photometric color index

Photometric color index (PCI) of frying oils were determined using the AOCS Cc 13c-50 Official Method[14].

2.4.7 Fatty acid composition

The methyl esters of the fatty acids were prepared according to International Union of Pure and Applied Chemistry (IUPAC) method[15] and analyzed with a gas chromatograph (GC 2010, Shimadzu, Kyoto, Japan) coupled with flame ionization detector (FID). Chromatographic separation of fatty acids was performed using a DB-23 silica capillary column (60 m length, 0.25 mm inner diameter and 0.25 μm film thickness, J&W Scientific, USA). Injector, column and detector temperatures were 230, 195 and 240℃, respectively. The carrier gas was helium at 1.0 mL/min ratio. 1 μL of sample was injected by the autosampler with a split mode (split ratio of 80:1).

2.4.8 α-Tocopherol composition

The α-tocopherol content of the frying oils were determined using an HPLC instrument (Shimadzu, Kyoto, Japan) equipped with UV-detector. The separation of the peaks was achieved using InertSustain NH_2 column (250 mm × 4.6 mm, 5 μm particle size, GL Sciences, Tokyo, Japan). The mobile phase was *n*-hexane:iso-propanol (99.5:0.5) with a flow rate of 1.5 mL/min. The detection wavelength was 290 nm and the injection volume was 20 μl. The α-tocopherol amounts of the samples were determined using a calibration curve.

2.4.9 3-MCPD and glycidyl esters

The 3-MCPD and glycidyl ester contents of the samples were determined according to the DGF C VI 18-10 Standard Method[16]. Quantification was performed according to the method offered by Cheng *et al.*[17] using gas chromatography-mass spectrometry instrument (Shimadzu QP2020, Shimadzu, Kyoto, Japan). The chromatographic separation was achieved with HP-5MS capillary column (30 m length, 0.32 mm inner diameter and 0.25 μm film thickness, J&W Scientific, USA). The carrier gas was helium with a flow rate of 1.18 mL/min. 1 μL of sample was injected by the autosampler using the splitless injection mode. The oven temperature was programmed from 80℃ to 155℃ at a rate of 5℃/min and increased to 300℃ at a rate of 15℃/min, and held for 5 min. The mass spectrometer was operated in selected ion monitoring mode with positive electron ionization (EI+) at an ionization voltage of 70 eV. The temperature of the ion source and interface in the mass spectrometer was 200 and 280℃, respectively. The ion traces *m/z* 147 and 150 were selected as the quantitative ions for the quantitation of 3-MCPD and 3-MCPD-d5, respectively. Limit of detection (LOD) value and limit of quantification (LOQ) values were 0.045 and 0.090, respectively.

2.4.10 Statistical analysis

Statistical analysis was carried out using SPSS 15.0 packaged software (SPSS Inc., Chicago, USA). The variance analysis technique (ANOVA) was used to determine the difference between the group means ($p < 0.05$) and the significance level of the difference was determined by Duncan multiple comparison test. Data were also processed by principal component analysis using XLSTAT 2019 version (Addinsoft, New York, NY, USA).

3 Results and Discussion

Different analytical techniques are needed to investigate the chemical reactions during frying[18]. Peroxide values, spectrophotometric indices at 232 and 270 nm, and *p*-anisidine values were measured to monitor the degree of oxidation of oil samples and the results were presented in Table 1.

Peroxide value is a measure of content of hydroperoxides which are primary products of oxidation reaction. The peroxide values of fresh oils were 6.53, 6.49, 5.25 and 2.56 for RSO, RSO:ROPO (80:20), RSO:ROPO (50:50) and ROPO in the same order, within the acceptable range for vegeta-

Table 1 The change oxidation parameters of oils throughout frying.

	Oil	Frying time (h)						
		0	4	8	12	16	20	24
PV (meq O_2/kg)	RSO	$6.53^{aC} \pm 0.05$	$28.78^{fD} \pm 0.31$	$20.72^{eB} \pm 0.30$	$15.58^{cA} \pm 0.07$	$16.69^{dA} \pm 0.41$	$15.70^{cA} \pm 0.07$	$12.48^{bA} \pm 0.56$
	RSO:ROPO (80:20 v/v)	$6.49^{aC} \pm 0.09$	$26.72^{fC} \pm 0.56$	$26.42^{fD} \pm 0.10$	$19.91^{eB} \pm 0.96$	$18.39^{bB} \pm 0.11$	$21.01^{dB} \pm 0.18$	$22.62^{eC} \pm 0.39$
	RSO:ROPO (50:50 v/v)	$5.25^{aB} \pm 0.04$	$24.47^{eB} \pm 0.72$	$22.26^{dC} \pm 0.07$	$20.72^{dB} \pm 1.69$	$21.60^{dC} \pm 1.05$	$15.90^{cA} \pm 0.47$	$13.14^{bA} \pm 0.04$
	ROPO	$2.5^{aA} \pm 0.08$	$14.87^{bA} \pm 0.72$	$19.36^{cdA} \pm 0.10$	$18.92^{cB} \pm 1.35$	$19.40^{cdB} \pm 0.45$	$21.03^{eB} \pm 0.18$	$20.30^{deB} \pm 0.26$
p-anisidine	RSO	$1.40^{aA} \pm 0.56$	$18.63^{bA} \pm 0.25$	$33.10^{eA} \pm 0.14$	$40.81^{dA} \pm 0.91$	$52.11^{eA} \pm 1.56$	$72.27^{fA} \pm 3.14$	$74.92^{gA} \pm 0.94$
	RSO:ROPO (80:20 v/v)	$2.23^{aB} \pm 0.34$	$16.34^{bA} \pm 2.12$	$24.23^{eB} \pm 2.39$	$24.66^{eC} \pm 1.39$	$35.47^{dB} \pm 1.49$	$47.80^{eB} \pm 0.06$	$64.26^{fB} \pm 1.07$
	RSO:ROPO (50:50 v/v)	$1.81^{aAB} \pm 0.28$	$17.99^{bA} \pm 0.59$	$32.26^{eA} \pm 2.21$	$37.99^{eB} \pm 0.49$	$34.03^{dB} \pm 0.81$	$36.60^{eC} \pm 0.18$	$46.29^{fC} \pm 0.23$
	ROPO	$3.62^{aC} \pm 0.35$	$7.97^{bB} \pm 0.23$	$15.96^{cC} \pm 0.86$	$14.75^{cD} \pm 0.81$	$22.04^{dC} \pm 0.13$	$22.77^{dD} \pm 2.12$	$31.74^{eD} \pm 0.12$
K_{232}	RSO	$7.40^{aA} \pm 0.30$	$9.95^{bA} \pm 0.83$	$12.39^{cA} \pm 0.73$	$15.89^{dA} \pm 2.53$	$16.37^{eA} \pm 1.40$	$19.28^{fA} \pm 1.07$	$21.29^{gA} \pm 0.82$
	RSO:ROPO (80:20 v/v)	$6.66^{aB} \pm 0.39$	$9.80^{bA} \pm 0.34$	$12.29^{cA} \pm 0.01$	$14.29^{dA} \pm 0.16$	$15.51^{fA} \pm 0.17$	$15.02^{eB} \pm 0.32$	$16.99^{gB} \pm 0.08$
	RSO:ROPO (50:50 v/v)	$5.57^{aC} \pm 0.17$	$8.62^{bB} \pm 0.23$	$9.52^{bB} \pm 0.37$	$10.16^{bB} \pm 0.73$	$12.45^{cB} \pm 0.82$	$14.52^{dB} \pm 2.25$	$13.23^{cdC} \pm 0.79$
	ROPO	$4.14^{aD} \pm 0.14$	$5.10^{bC} \pm 0.09$	$6.14^{cC} \pm 0.15$	$6.67^{dC} \pm 0.11$	$9.50^{eC} \pm 0.16$	$10.37^{fC} \pm 0.33$	$11.25^{gD} \pm 0.61$
K_{270}	RSO	$3.62^{aA} \pm 0.01$	$4.19^{bA} \pm 0.11$	$4.84^{cA} \pm 0.16$	$5.02^{dA} \pm 0.07$	$5.26^{dA} \pm 0.07$	$5.48^{eA} \pm 0.17$	$5.65^{fA} \pm 0.10$
	RSO:ROPO (80:20 v/v)	$3.09^{aB} \pm 0.05$	$3.75^{bB} \pm 0.13$	$4.15^{cB} \pm 0.04$	$4.43^{dB} \pm 0.12$	$4.95^{eB} \pm 0.20$	$5.08^{efB} \pm 0.08$	$5.24^{fB} \pm 0.14$
	RSO:ROPO (50:50 v/v)	$2.71^{aC} \pm 0.07$	$3.80^{bB} \pm 0.34$	$4.34^{cB} \pm 0.30$	$4.53^{cdB} \pm 0.07$	$5.20^{eA} \pm 0.19$	$4.77^{dC} \pm 0.11$	$5.15^{eB} \pm 0.28$
	ROPO	$1.59^{aD} \pm 0.10$	$1.96^{bC} \pm 0.08$	$2.48^{cC} \pm 0.24$	$2.30^{cC} \pm 0.15$	$2.65^{dC} \pm 0.11$	$2.28^{cD} \pm 0.08$	$1.90^{bC} \pm 0.10$

a-g: Different lowercase superscript letters indicate significant differences between frying times for the same oil ($p < 0.05$).
A-D: Different uppercase superscript letters indicate significant differences between oils for the same frying time ($p < 0.05$).
PV: Peroxide value, K_{232} and K_{270}: spectrophotometric indices at 232 and 270 nm

ble oils (≤ 10 meq O_2/kg oil) according to Turkish Food Codex[19]. During frying, peroxide indexes of RSO and its blends increased to a maximum value and then decreased to the end of the process. Peak values were 28.78 meq O_2/kg oil for RSO, 26.72 meq O_2/kg oil for RSO:ROPO (80:20) and 24.47 meq O_2/kg oil for RSO:ROPO (50:50). The similar pattern was also reported in previously published studies[20, 21]. Hydroperoxides are known to be unstable and they decompose into secondary oxidation products during frying[22]. The increasing rate of hydroperoxides was slower for ROPO. The peroxide value of ROPO increased gradually and reached 20.30 meq O_2/kg oil in the 24th cycle.

As explained above, peroxide value alone is not a reliable representative of the extent of oxidation during frying. A great variety of volatile and non-volatile compounds are generated as a result of thermal degradation of hydroperoxides. *p*-anisidine value is a measure of secondary oxidative compounds namely non-volatile aldehydes (mainly 2-alkenal and 2,4-dienal) and should be taken into consideration for a better evaluation of oxidation during frying process[1]. Based on Table 1, the *p*-anisidine values of all oils significantly increased throughout the process, due to the formation of secondary oxidation products. Similar increases in *p*-anisidine values of oils were reported in previous works[23, 24]. Before frying, the highest *p*-anisidine value was observed for ROPO (3.62), while RSO showed the lowest initial value (1.40). However, at the end of 3 days of frying operation, RSO reached the maximum value (74.92) among all oils, where ROPO had the lowest value (31.74). The results have verified that pure RSO is more prone to oxidation at high frying temperatures than the blend oils, because of the presence of high amounts of PUFAs, related with the generation of oxidation products.

The ultraviolet spectrophotometric index at 232 is an indicator of conjugated diene formation that occurs as a result of PUFA degradation, whereas K_{270} correlates with secondary oxidative products such as conjugated trienes and carbonyl compounds. UV absorbances at 232 nm were detected to increase substantially for all oils as frying progressed (Table 1). The highest increment was observed in RSO and followed by RSO:ROPO (80:20), RSO:ROPO (50:50), ROPO sequentially. A comparable trend was also observed for absorptivity at 270 nm. ROPO contained relatively lower percentage of linoleic acid and hence accumulated less conjugated dienes and trienes. The increase in conjugated dienes and trienes with the continued frying period is consistent with the former literature[25].

The free acidity values, photometric color indexes, total polar contents and α-tocopherol concentrations of oils during frying were given in Table 2.

Free acidity indicates the levels of free fatty acids in the oil that are formed by the hydrolysis through the breakdown of triacylglycerols. The conventional measurement of free fatty acids (FFA) is an important indicator of hydrolytic deterioration and oil quality. Free fatty acidity level of frying oils increase when the water released from the food being fried reacts with the triglycerides[26]. As given in Table 2, free acidity of oils increased significantly with the increasing number of frying cycles, in accordance with former works[27, 28]. The initial FFA were the same (0.18%)

Table 2 The change in free acidity, PCI, TPC and α-tocopherol contents of oils throughout frying.

	Oil	Frying time (h)						
		0	4	8	12	16	20	24
Free acidity (%)	RSO	$0.18^{aA} \pm 0.00$	$0.27^{bB} \pm 0.00$	$0.27^{bB} \pm 0.00$	$0.35^{cC} \pm 0.01$	$0.36^{cC} \pm 0.00$	$0.41^{cA} \pm 0.06$	$0.42^{cA} \pm 0.09$
	RSO:ROPO (80:20 v/v)	$0.18^{aAB} \pm 0.00$	$0.18^{aA} \pm 0.00$	$0.18^{aA} \pm 0.00$	$0.20^{aA} \pm 0.05$	$0.27^{bB} \pm 0.00$	$0.27^{bB} \pm 0.00$	$0.36^{cA} \pm 0.00$
	RSO:ROPO (50:50 v/v)	$0.18^{aA} \pm 0.00$	$0.18^{aA} \pm 0.00$	$0.18^{aA} \pm 0.00$	$0.27^{bB} \pm 0.00$	$0.27^{bB} \pm 0.00$	$0.27^{bB} \pm 0.00$	$0.37^{cA} \pm 0.00$
	ROPO	$0.18^{aA} \pm 0.00$	$0.18^{aA} \pm 0.00$	$0.18^{aA} \pm 0.00$	$0.18^{aA} \pm 0.00$	$0.27^{bA} \pm 0.00$	$0.27^{bB} \pm 0.00$	$0.36^{cA} \pm 0.00$
PCI	RSO	$-0.27^{aA} \pm 0.12$	$0.12^{bA} \pm 0.08$	$0.36^{cA} \pm 0.09$	$0.37^{cA} \pm 0.10$	$0.66^{dA} \pm 0.14$	$0.62^{dA} \pm 0.13$	$0.86^{eA} \pm 0.16$
	RSO:ROPO (80:20 v/v)	$1.10^{bB} \pm 0.04$	$0.85^{aB} \pm 0.04$	$0.91^{aB} \pm 0.07$	$1.21^{cB} \pm 0.06$	$1.24^{cB} \pm 0.05$	$1.22^{cA} \pm 0.00$	$1.55^{dA} \pm 0.08$
	RSO:ROPO (50:50 v/v)	$2.89^{abC} \pm 0.24$	$2.59^{aC} \pm 0.26$	$2.67^{aC} \pm 0.05$	$2.87^{abC} \pm 0.09$	$3.27^{bB} \pm 0.56$	$3.23^{bB} \pm 0.32$	$3.31^{bA} \pm 0.23$
	ROPO	$7.73^{aD} \pm 0.92$	$7.09^{abD} \pm 0.33$	$6.99^{abD} \pm 0.28$	$7.02^{abD} \pm 0.51$	$7.28^{aC} \pm 1.31$	$7.64^{aC} \pm 0.88$	$5.84^{bB} \pm 0.86$
TPC (%)	RSO	$12.5^{aA} \pm 0.0$	$15.8^{bA} \pm 0.4$	$18.0^{cA} \pm 0.0$	$19.5^{dA} \pm 0.7$	$21.3^{eA} \pm 0.4$	$22.0^{fA} \pm 0.0$	$24.5^{gA} \pm 0.7$
	RSO:ROPO (80:20 v/v)	$11.0^{aB} \pm 0.0$	$14.0^{bB} \pm 0.0$	$16.3^{cB} \pm 0.4$	$18.3^{dB} \pm 0.4$	$19.5^{eB} \pm 0.0$	$19.5^{eB} \pm 0.0$	$21.5^{fB} \pm 0.0$
	RSO:ROPO (50:50 v/v)	$9.5^{aC} \pm 0.0$	$11.5^{bC} \pm 0.0$	$13.5^{cC} \pm 0.0$	$15.0^{dC} \pm 0.4$	$15.5^{eC} \pm 0.4$	$16.5^{fC} \pm 0.0$	$19.0^{gC} \pm 0.7$
	ROPO	$6.5^{aD} \pm 0.0$	$7.5^{bD} \pm 0.0$	$9.0^{cD} \pm 0.0$	$10.0^{dD} \pm 0.0$	$10.5^{eD} \pm 0.0$	$11.5^{fD} \pm 0.0$	$12.5^{gD} \pm 0.0$
α-tocopherol (mg/kg)	RSO	$645.38^{aA} \pm 6.22$	$494.72^{bA} \pm 10.83$	$416.77^{cA} \pm 32.45$	$364.76^{dA} \pm 34.78$	$312.53^{eA} \pm 43.72$	$260.13^{fA} \pm 40.11$	$234.25^{fA} \pm 38.45$
	RSO:ROPO (80:20 v/v)	$559.29^{aB} \pm 18.40$	$402.64^{bB} \pm 5.23$	$283.85^{cB} \pm 38.82$	$252.47^{cB} \pm 21.71$	$199.56^{dB} \pm 45.79$	$203.61^{dB} \pm 4.86$	$84.59^{eB} \pm 31.86$
	RSO:ROPO (50:50 v/v)	$435.32^{aC} \pm 15.56$	$187.52^{bC} \pm 20.74$	$193.11^{bC} \pm 6.37$	$123.83^{cC} \pm 3.42$	$114.30^{cB} \pm 11.26$	$81.25^{dC} \pm 32.20$	$71.60^{dB} \pm 4.98$
	ROPO	$183.48^{aD} \pm 17.59$	$118.89^{bD} \pm 9.48$	$35.90^{cD} \pm 2.53$	$23.14^{cdD} \pm 3.50$	$17.53^{dC} \pm 5.91$	$16.69^{dD} \pm 2.98$	$16.40^{dC} \pm 4.76$

a-g: Different lowercase superscript letters indicate significant differences between frying times for the same oil ($p < 0.05$).
A-D: Different uppercase superscript letters indicate significant differences between oils for the same frying time ($p < 0.05$).
PCI: Photometric color index, TPC: Total polar compounds

for all oils, however the highest increase was the detected for RSO. The inclusion of ROPO to frying medium enabled slower rate of FFA accumulation throughout frying when compared to RSO.

The color measurement is another tool to assess the quality of the oils during frying since non-volatile degradation products such as oxidized triacylglycerols and FFA accumulate in the oil and cause an increase in color intensity[2]. The photometric color indices of oils of the current work in the time of frying was as follows in descending order: ROPO＞RSO:ROPO(50:50)＞RSO:ROPO(80:20)＞RSO. During the process, slight and statistically significant increases in color indices were observed for RSO and its blends; however the similar increment was not monitored for ROPO, which may point a lower degree of degradation. The increase rate of color values was the fastest for RSO and the color stabilities of the oils were found to correlate with the ROPO ratio in the mix system. Ben Hammouda *et al.*[29] also reported an increase in color intensity of oils during frying reflecting overall chemical degradation and polymerization.

Quantitative evaluation of total polar compounds(TPC) is one of the most reliable and accurate assessment of thermal degradation of frying oils. TPC correspond to newly formed components which have higher polarity than that of triacylglycerols[3]. Previous researches have displayed the toxicity of polar compounds to laboratory animals[30], therefore, many countries have established a regulatory maximum limit around 25% for TPC. The initial TPC values of RSO, ROPO and their binary blends varied in 6.5-12.5%(Table 2). As expected, TPC increased linearly with frying time in accordance with formerly reported data for frying fats. After 24 h of frying, TPC reached 24.5% for RSO, 21.5% for RSO:ROPO(80:20), 19.0% for RSO:ROPO(50:50)and 12.5% for ROPO. None of the oils exceeded the regulatory discarding limit of 25% determined by Turkish Food Codex[19]. However, the results have shown that RSO could be used for frying potato sticks up to 3 days. TPC was determined to be higher when the degree of unsaturation increased and the blended oils showed better performance than pure RSO. High oleic oils have been previously reported to show a lower level of polar compound formation when compared to lower oleic containing ones during frying[31].

Vitamin E, particularly α-tocopherol is an important minor component of vegetable oils and contributes to antioxidant properties and nutritional values of the oil. The fresh RSO and ROPO had α-tocopherol contents of 645.38 mg/kg and 183.48 mg/kg respectively. During frying, α-tocopherol contents decreased gradually for all types of oils(Table 2). The rapid decrease in α-tocopherol content was because of its protective effect throughout thermal degradation of oil samples. α-tocopherol loss was found to be highest in ROPO(91.06%), followed by RSO:ROPO(80:20)(84.88%), RSO:ROPO(50:50)(83.55%)and RSO(63.70%). The marked losses in tocopherols throughout frying process have also been reported in formerly published works[23, 32].

Evaluation of the fatty acid composition is the most important issue in determining the stability of frying oils. The fatty acid composition of RSO, ROPO and their blends before and after frying are given in Table 3. Fresh RSO was

Table 3 The change in fatty acid composition of oils throughout frying.

Frying time (h)	Fatty acids (%)											
	C14:0	C16:0	C16:1	C17:0	C17:1	C18:0	C18:1	C18:2	C18:3	C20:0	C20:1	C18:2/C16:0
	RSO											
0	$0.08^{aC} \pm 0.00$	$5.85^{aA} \pm 0.12$	$0.37^{abB} \pm 0.03$	$0.02^{aA} \pm 0.01$	$0.01^{aA} \pm 0.00$	$2.27^{abA} \pm 0.15$	$11.41^{aA} \pm 0.12$	$76.21^{aD} \pm 0.82$	$2.99^{bC} \pm 0.73$	$0.80^{aA} \pm 0.16$	$0.14^{abcA} \pm 0.03$	$13.06^{cD} \pm 0.06$
4	$0.08^{abC} \pm 0.01$	$6.06^{abA} \pm 0.20$	$0.42^{abC} \pm 0.07$	$0.03^{aA} \pm 0.00$	$0.01^{aA} \pm 0.00$	$2.25^{abA} \pm 0.19$	$11.54^{aA} \pm 0.10$	$75.72^{aA} \pm 1.37$	$2.63^{cC} \pm 0.35$	$0.81^{aB} \pm 0.06$	$0.18^{abcA} \pm 0.01$	$12.49^{dD} \pm 0.18$
8	$0.09^{abC} \pm 0.00$	$6.48^{cdA} \pm 0.20$	$0.37^{aA} \pm 0.16$	$0.03^{aA} \pm 0.00$	$0.01^{aA} \pm 0.00$	$2.02^{aA} \pm 0.14$	$11.69^{abA} \pm 0.32$	$76.15^{aA} \pm 1.14$	$2.23^{abC} \pm 0.10$	$0.15^{bA} \pm 0.03$	$0.07^{abA} \pm 0.03$	$11.75^{cD} \pm 0.21$
12	$0.09^{abC} \pm 0.01$	$6.26^{bcA} \pm 0.03$	$0.52^{bcB} \pm 0.10$	$0.02^{aA} \pm 0.00$	$0.01^{aA} \pm 0.00$	$2.29^{abA} \pm 0.03$	$11.87^{bcA} \pm 0.03$	$74.05^{bA} \pm 0.22$	$3.84^{cC} \pm 0.26$	$0.83^{aC} \pm 0.06$	$0.20^{cA} \pm 0.06$	$11.75^{cD} \pm 0.21$
16	$0.10^{bC} \pm 0.01$	$6.64^{dA} \pm 0.12$	$0.61^{cB} \pm 0.08$	$0.03^{aA} \pm 0.01$	$0.01^{aA} \pm 0.00$	$2.14^{aA} \pm 0.21$	$11.99^{cA} \pm 0.22$	$74.20^{bD} \pm 0.52$	$3.36^{cC} \pm 0.46$	$0.76^{aC} \pm 0.07$	$0.16^{bcA} \pm 0.01$	$11.82^{cD} \pm 0.07$
20	$0.12^{cC} \pm 0.04$	$6.96^{eA} \pm 0.35$	$0.42^{abB} \pm 0.14$	$0.03^{aA} \pm 0.01$	$0.01^{aA} \pm 0.00$	$2.56^{bA} \pm 0.39$	$12.63^{dA} \pm 0.27$	$74.11^{bD} \pm 0.91$	$3.07^{bcC} \pm 0.58$	$0.75^{aB} \pm 0.27$	$0.15^{abcA} \pm 0.05$	$11.17^{bD} \pm 0.13$
24	$0.10^{bcC} \pm 0.01$	$7.33^{fA} \pm 0.18$	$0.47^{abcC} \pm 0.66$	$0.03^{aA} \pm 0.00$	$0.01^{aA} \pm 0.00$	$2.51^{bAB} \pm 0.25$	$12.85^{dA} \pm 0.19$	$74.95^{abD} \pm 0.73$	$2.02^{aC} \pm 0.62$	$0.20^{bA} \pm 0.03$	$0.07^{aA} \pm 0.01$	$10.23^{aD} \pm 0.17$
	RSO:ROPO (80:20 v/v)											
0	$0.08^{aC} \pm 0.00$	$7.68^{aB} \pm 0.01$	$0.16^{aA} \pm 0.00$	$0.06^{bB} \pm 0.00$	$0.05^{abB} \pm 0.01$	$2.58^{bB} \pm 0.01$	$23.69^{bB} \pm 0.14$	$65.00^{dC} \pm 0.14$	$0.17^{aA} \pm 0.01$	$0.36^{aA} \pm 0.01$	$0.16^{cA} \pm 0.00$	$8.45^{eC} \pm 0.02$
4	$0.08^{bC} \pm 0.00$	$7.77^{bB} \pm 0.01$	$0.15^{aA} \pm 0.00$	$0.06^{abB} \pm 0.00$	$0.04^{aB} \pm 0.01$	$2.56^{aAB} \pm 0.02$	$23.06^{aB} \pm 0.18$	$65.59^{eC} \pm 0.18$	$0.17^{aA} \pm 0.01$	$0.37^{abA} \pm 0.01$	$0.15^{abcAB} \pm 0.00$	$8.43^{eC} \pm 0.04$
8	$0.08^{bC} \pm 0.00$	$8.01^{cB} \pm 0.01$	$0.15^{aA} \pm 0.00$	$0.06^{abB} \pm 0.00$	$0.04^{abB} \pm 0.00$	$2.57^{abBC} \pm 0.01$	$23.44^{aB} \pm 0.03$	$64.98^{dC} \pm 0.06$	$0.16^{aA} \pm 0.01$	$0.37^{abC} \pm 0.00$	$0.15^{aB} \pm 0.00$	$8.11^{dC} \pm 0.02$
12	$0.09^{cC} \pm 0.00$	$8.24^{dB} \pm 0.02$	$0.16^{aA} \pm 0.00$	$0.06^{abB} \pm 0.00$	$0.04^{abB} \pm 0.01$	$2.61^{cC} \pm 0.01$	$24.14^{cB} \pm 0.25$	$63.98^{cC} \pm 0.27$	$0.17^{aA} \pm 0.00$	$0.37^{abB} \pm 0.00$	$0.15^{abcA} \pm 0.01$	$7.76^{cC} \pm 0.04$
16	$0.10^{dC} \pm 0.00$	$8.49^{eB} \pm 0.01$	$0.20^{bA} \pm 0.04$	$0.05^{aB} \pm 0.00$	$0.04^{abB} \pm 0.01$	$2.65^{dBC} \pm 0.01$	$24.29^{cB} \pm 0.30$	$63.49^{bC} \pm 0.30$	$0.17^{aA} \pm 0.01$	$0.37^{abB} \pm 0.02$	$0.16^{bcA} \pm 0.01$	$7.48^{bC} \pm 0.04$
20	$0.10^{eBC} \pm 0.00$	$8.56^{fB} \pm 0.01$	$0.16^{aA} \pm 0.00$	$0.06^{abB} \pm 0.00$	$0.04^{abB} \pm 0.00$	$2.65^{dA} \pm 0.01$	$24.14^{cA} \pm 0.03$	$63.63^{bC} \pm 0.04$	$0.16^{aA} \pm 0.01$	$0.37^{abA} \pm 0.01$	$0.15^{abcA} \pm 0.00$	$7.43^{bC} \pm 0.01$
24	$0.10^{fC} \pm 0.00$	$8.80^{gB} \pm 0.01$	$0.16^{aA} \pm 0.00$	$0.05^{abB} \pm 0.00$	$0.05^{bB} \pm 0.01$	$2.68^{eBC} \pm 0.01$	$24.40^{cB} \pm 0.06$	$63.06^{aC} \pm 0.06$	$0.15^{aA} \pm 0.01$	$0.38^{bC} \pm 0.01$	$0.15^{abB} \pm 0.00$	$7.16^{aC} \pm 0.01$
	RSO:ROPO (50:50 v/v)											
0	$0.06^{aB} \pm 0.00$	$9.31^{aC} \pm 0.02$	$0.30^{bAB} \pm 0.00$	$0.08^{aC} \pm 0.00$	$0.10^{abC} \pm 0.02$	$2.61^{aB} \pm 0.01$	$40.89^{aC} \pm 0.05$	$45.77^{fB} \pm 0.07$	$0.30^{bAB} \pm 0.01$	$0.39^{aA} \pm 0.00$	$0.20^{bA} \pm 0.01$	$4.91^{gB} \pm 0.02$
4	$0.06^{abB} \pm 0.00$	$9.52^{bC} \pm 0.03$	$0.30^{abB} \pm 0.00$	$0.08^{aC} \pm 0.00$	$0.12^{bcC} \pm 0.02$	$2.61^{aC} \pm 0.01$	$41.18^{bC} \pm 0.08$	$45.27^{eB} \pm 0.10$	$0.28^{aA} \pm 0.02$	$0.40^{abA} \pm 0.00$	$0.20^{abB} \pm 0.00$	$4.75^{fB} \pm 0.02$
8	$0.07^{cdB} \pm 0.01$	$9.78^{cC} \pm 0.06$	$0.30^{bA} \pm 0.00$	$0.08^{aC} \pm 0.00$	$0.09^{aC} \pm 0.01$	$2.67^{cC} \pm 0.02$	$41.33^{cC} \pm 0.07$	$44.80^{dB} \pm 0.14$	$0.28^{abA} \pm 0.02$	$0.40^{abC} \pm 0.01$	$0.20^{bC} \pm 0.01$	$4.58^{eB} \pm 0.04$
12	$0.07^{bcB} \pm 0.00$	$9.90^{dC} \pm 0.01$	$0.29^{aA} \pm 0.00$	$0.08^{aC} \pm 0.00$	$0.08^{aC} \pm 0.01$	$2.64^{bC} \pm 0.01$	$41.57^{dC} \pm 0.06$	$44.50^{eB} \pm 0.08$	$0.27^{aA} \pm 0.00$	$0.40^{abB} \pm 0.01$	$0.19^{abA} \pm 0.00$	$4.49^{dB} \pm 0.01$
16	$0.07^{cdB} \pm 0.00$	$10.13^{eC} \pm 0.01$	$0.29^{aA} \pm 0.00$	$0.08^{aC} \pm 0.00$	$0.13^{cC} \pm 0.01$	$2.67^{cC} \pm 0.01$	$41.84^{eC} \pm 0.03$	$43.93^{bB} \pm 0.03$	$0.26^{aA} \pm 0.00$	$0.40^{bB} \pm 0.01$	$0.19^{aB} \pm 0.00$	$4.33^{cB} \pm 0.01$
20	$0.07^{cdB} \pm 0.00$	$10.20^{fC} \pm 0.02$	$0.29^{aAB} \pm 0.01$	$0.08^{aC} \pm 0.00$	$0.13^{cC} \pm 0.02$	$2.67^{cA} \pm 0.00$	$41.87^{eA} \pm 0.12$	$43.82^{bB} \pm 0.11$	$0.26^{aB} \pm 0.01$	$0.40^{abA} \pm 0.00$	$0.19^{abB} \pm 0.00$	$4.29^{bB} \pm 0.01$
24	$0.08^{dB} \pm 0.00$	$10.43^{gC} \pm 0.02$	$0.30^{abB} \pm 0.00$	$0.08^{aC} \pm 0.00$	$0.14^{cD} \pm 0.02$	$2.71^{dC} \pm 0.01$	$42.04^{fC} \pm 0.06$	$43.37^{aB} \pm 0.05$	$0.27^{aAB} \pm 0.01$	$0.40^{abC} \pm 0.00$	$0.19^{abC} \pm 0.00$	$4.15^{aB} \pm 0.01$
	ROPO											
0	$0.01^{aA} \pm 0.00$	$11.31^{aD} \pm 0.09$	$1.14^{aC} \pm 0.19$	$0.09^{aC} \pm 0.01$	$0.13^{bD} \pm 0.01$	$2.47^{abB} \pm 0.04$	$68.76^{aD} \pm 0.31$	$14.65^{aA} \pm 0.30$	$0.96^{aB} \pm 0.10$	$0.29^{aA} \pm 0.03$	$0.20^{aA} \pm 0.01$	$1.29^{aA} \pm 0.04$
4	$0.02^{abA} \pm 0.00$	$11.37^{aD} \pm 0.24$	$1.17^{aC} \pm 0.10$	$0.08^{aD} \pm 0.01$	$0.13^{bC} \pm 0.01$	$2.43^{aB} \pm 0.08$	$68.42^{aD} \pm 0.95$	$14.96^{aD} \pm 1.03$	$0.96^{aB} \pm 0.43$	$0.27^{aA} \pm 0.03$	$0.18^{aAB} \pm 0.02$	$1.31^{aA} \pm 0.12$
8	$0.03^{bcA} \pm 0.00$	$11.62^{abD} \pm 0.08$	$1.20^{aB} \pm 0.28$	$0.08^{aD} \pm 0.01$	$0.13^{bD} \pm 0.01$	$2.46^{abB} \pm 0.06$	$68.55^{aD} \pm 0.60$	$14.63^{aA} \pm 0.51$	$0.84^{aB} \pm 0.26$	$0.27^{aB} \pm 0.03$	$0.18^{aC} \pm 0.02$	$1.25^{aA} \pm 0.05$
12	$0.03^{cA} \pm 0.01$	$11.91^{bcD} \pm 0.06$	$1.18^{aC} \pm 0.16$	$0.08^{aC} \pm 0.01$	$0.12^{abD} \pm 0.02$	$2.53^{bB} \pm 0.06$	$68.78^{aD} \pm 0.38$	$14.14^{aA} \pm 0.34$	$0.65^{aB} \pm 0.18$	$0.28^{aA} \pm 0.01$	$0.18^{aA} \pm 0.02$	$1.20^{aA} \pm 0.01$
16	$0.04^{cdA} \pm 0.01$	$11.88^{bcD} \pm 0.12$	$1.10^{aC} \pm 0.18$	$0.09^{aC} \pm 0.00$	$0.13^{abC} \pm 0.00$	$2.49^{abB} \pm 0.03$	$68.58^{aD} \pm 0.59$	$14.43^{aA} \pm 0.32$	$0.84^{aB} \pm 0.38$	$0.27^{aA} \pm 0.00$	$0.16^{aA} \pm 0.02$	$1.21^{aA} \pm 0.04$
20	$0.04^{cdA} \pm 0.00$	$11.94^{bcD} \pm 0.07$	$1.34^{aC} \pm 0.16$	$0.07^{aC} \pm 0.01$	$0.11^{aC} \pm 0.02$	$2.46^{abA} \pm 0.01$	$68.15^{aA} \pm 0.50$	$14.57^{aA} \pm 0.26$	$0.87^{aB} \pm 0.19$	$0.26^{aA} \pm 0.01$	$0.17^{aAB} \pm 0.01$	$1.22^{aA} \pm 0.03$
24	$0.05^{dA} \pm 0.01$	$12.19^{cD} \pm 0.37$	$1.32^{aD} \pm 0.07$	$0.08^{aC} \pm 0.01$	$0.12^{abC} \pm 0.02$	$2.45^{abA} \pm 0.05$	$68.29^{aD} \pm 1.15$	$14.35^{aA} \pm 1.24$	$0.97^{aB} \pm 0.41$	$0.26^{aB} \pm 0.02$	$0.17^{aBC} \pm 0.03$	$1.19^{aA} \pm 0.15$

a-g: Different superscript letters indicate significant differences between frying times for the same oil ($p < 0.05$).
A-D: Different superscript letters indicate significant differences between fatty acids of different oils for the same frying time ($p < 0.05$).

Table 4 3-MCPD and GE levels of oils before and after 3 days of frying (mg/kg).

Oil	3-MCPD-E		GE	
	0.h	24.h	0.h	24.h
RSO	$0.34^{aA} \pm 0.03$	$0.26^{bA} \pm 0.03$	$0.04^{aA} \pm 0.02$	$0.10^{bA} \pm 0.01$
RSO:ROPO (80:20 v/v)	$0.49^{aB} \pm 0.02$	$0.33^{bB} \pm 0.01$	$0.21^{aB} \pm 0.06$	$0.11^{bA} \pm 0.02$
RSO:ROPO (50:50 v/v)	$0.73^{aC} \pm 0.08$	$0.59^{bC} \pm 0.00$	$0.26^{aB} \pm 0.05$	$0.32^{bB} \pm 0.04$
ROPO	$1.38^{aD} \pm 0.10$	$0.84^{bD} \pm 0.04$	$0.36^{aC} \pm 0.03$	$0.32^{aB} \pm 0.06$

a-g: Different superscript letters indicate significant differences between frying times for the same oil ($p < 0.05$).

A-D: Different superscript letters indicate significant differences between oils for the same frying time ($p < 0.05$).

characterized by its high linoleic acid ratio (76.21%) followed by oleic (11.41%), palmitic (5.85%), linolenic (2.99%) and stearic (2.27%) acids. Eryılmaz *et al.*[33], reported 81% linoleic, 10.54% oleic, 6.10% palmitic, 1.60% stearic, 0.11% linolenic, 0.30% arachidic, 0.09% palmitoleic, 0.15% eicocenic and 0.08% myristic acid levels for safflower oil. ROPO was a good source of oleic acid (68.76%) and contained linoleic (14.65%), palmitic (11.31%), stearic (2.47%) acids as well. Ruiz-Méndez *et al.*[12] found that olive pomace oil contained 70.36-73.29% oleic, 11.10-12.02% palmitic, 9.19-11.46% linoleic, and 2.84-2.94 stearic acids in accordance with the present findings. RSO:ROPO (80:20) had 65.00% linoleic and 23.69% oleic acid; while RSO:ROPO (50:50) had more stabilized profile including 45.77% linoleic and 40.89% oleic acids. Blending RSO with ROPO decreased the linoleic and linolenic; meanwhile increased the oleic and palmitic acid ratio of blend oils. During frying, linoleic acid ratios of RSO and its blends decreased gradually although slight fluctuations were observed, because of the susceptibility of PUFAs to oxidation. As a consequence of this decrease, saturated fatty acid ratios were found to increase with prolonged frying time for the same oils as also stated in former works[3, 34]. Additionally, oleic acid percentages of RSO and its blends were found to increase probably due to the relative decrease in linoleic acids. However, the same pattern was not revealed by ROPO. The duration of frying time was found to be statistically insignificant on oleic and linoleic ratios, which is a clear indication of frying stability of ROPO.

The ratio of C18:2/C16:0 is a marker for the degree of oxidative degradation in frying oils. Linoleic acid is more prone to oxidation and palmitic acid is more resistant. The C18:2/C16:0 values were highest in RSO because of the large percentage of linoleic acid (Table 3). The ratio was found to decline during three consecutive days of frying for RSO and its blends. Comparable reductions were also described for C18:2/C16:0 ratio with frying in former similar works[35]. However, C18:2/C16:0 ratio of ROPO was not affected significantly during frying process. Blending RSO with increasing ratios of ROPO clearly improved the frying stability of single oil.

3-MCPD and GEs are heat induced food process contaminants that are widely found in refined vegetable oils. The compounds are potentially toxic to human health due to the release of 3-MCPD and glycidol from their esters in gastrointestinal tract. 3-MCPD and GEs are known to be accumulated mainly at deodorization step of oil refining. The latest researches have shown that these contaminants can be also formed through thermal processing such as frying and baking[36]. The 3-MCPD-E and GE levels of RSO, ROPO and their blends before and after frying are given in Table 4. The 3-MCPD-E levels of the frying oils were as follows in descending order at both 0th and 24th hours of frying: ROPO > RSO:ROPO (50:50) > RSO:ROPO (80:20) > RSO. ROPO contained 1.38 mg/kg and RSO had 0.34 mg/kg of 3-MCPD-Es. Ben Hammouda *et al.*[29] reported 1.10 mg/kg of 3-MCPD-E content for refined olive pomace oil. The frying process for 24 h caused significant decreases in 3-MCPD-E contents of all frying oils. The degradation of 3-MCPD-Es during prolonged frying were also reported in previous works[37]. During frying, 3-MCPD-Es have been reported to undergo a dynamic change between formation and degradation. Although some amount of esters are formed at the early periods of frying due to the presence of precursors and heat; the esters have been found to become unstable and their contents tend to decrease with prolonged frying[38]. The GE levels of frying oils were found to be lower than 3-MCPD-Es. The GE content of RSO was 0.04 mg/kg at the beginning of the process and reached to 0.10 mg/kg. A similar significant increase was also detected for RSO:ROPO (80:20) (from 0.26 to 0.32 mg/kg); however, the same trend was not observed for other two oils. The GE content of RSO:ROPO (50:50) decreased from 0.21 to 0.11 mg/kg by frying, meanwhile the level of the contaminant was observed to remain unchanged statistically. Former works have reported either increase[37], decrease[39] or constancy[40] by frying in GE amounts of oils.

Principal component analysis is multivariate technique

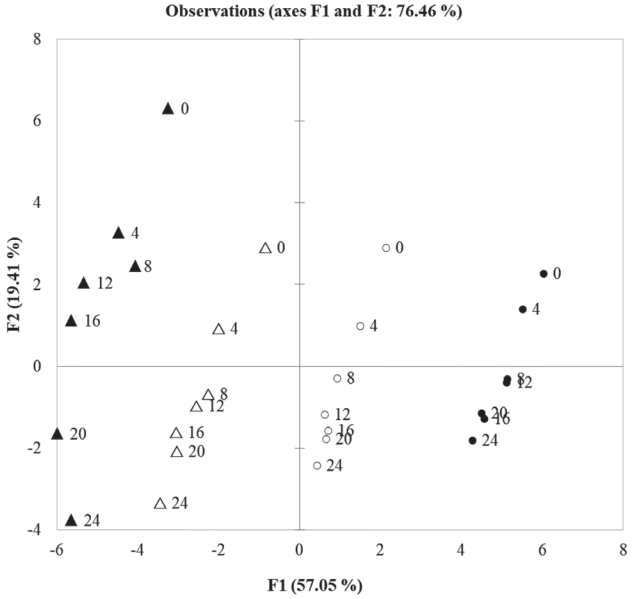


Fig. 1 Factor score plot of frying oils (RSO: filled triangle, RSO:ROPO (80:20): open triangle, RSO:ROPO (50:50): open circle, ROPO: filled circle, F1: Factor 1, F2: Factor2).

used for classification goals. In the current study, PCA was utilized to classify frying oils based on their quality and oxidative parameters and fatty acid profile. Data were arranged in a matrix containing four frying oils at seven frying periods. Factor score plot which shows distribution of data is given in Fig. 1. The first two factors, namely Factor 1 (F1) and Factor 2 (F2) explained 76.46% of the total variance (F1: 19.41%, F2: 57.05%). The score plot which shows the relations between oils reveal that ROPO and RSO:ROPO (50:50) had positive scores on Factor 1 , while RSO and RSO:ROPO (80:20) had negative. Clear discriminations and separate clusters were monitored between four frying oils with different compositions. The size of the clusters were observed to expand as the ratio of RSO increased in the oil.

4 Conclusion

The current study described the frying stability of RSO and the improvement in the stability by blending with different levels of ROPO. The chemical degradation indicators have shown that thermo-oxidation was the fastest in RSO. ROPO was detected to be more resistant to oxidative decomposition due to its monounsaturated nature. The addition of ROPO clearly reduced the degradation and improved the frying performance of binary blends. The findings of the current study have also demonstrated that ROPO was relatively rich of 3-MCPD and GEs in comparison with RSO. Blending of oils brought not only the advantage of a better fatty acid profile; but also diluted these undesired process contaminants. In view of the findings of the present study, it can be concluded that blending is a viable approach, since the blend oils have superior qualities than single specific oils. The use of RSO and ROPO blends is a promising possibility for increasing frying stability.

Acknowledgements

This research was supported by Aydın Adnan Menderes University Research Fund. Project Number: MF-18014.

References

1) Zribi, A.; Jabeur, H.; Matthäus, B.; Bouaziz, M. Quality control of refined oils mixed with palm oil during repeated deep-frying using FT-NIRS, GC, HPLC, and multivariate analysis. *Eur. J. Lipid Sci. Technol.* **118**, 512-523 (2016). doi:10.1002/ejlt.201500149
2) Naghshineh, M.; Ariffin, A.A.; Ghazali, H.M.; Mirhosseini, H.; Mohammad, A.S. Effect of saturated/unsaturated fatty acid ratio on physicochemical properties of palm olein–olive oil blend. *J. Am. Oil Chem. Soc.* **87**, 255-262 (2010). doi: 10.1007/s11746-009-1495-z
3) Ben Hammouda, I.; Triki, M.; Matthäus, B.; Bouaziz, M. A comparative study on formation of polar components, fatty acids and sterols during frying of refined olive pomace oil pure and its blend coconut oil. *J. Agric. Food Chem.* **66**, 3514-3523 (2018). doi: 10.1021/acs.jafc.7b05163
4) Khalid, N.; Khan, R.S.; Hussain, M.I.; Farooq, M.; Ahmad, A.; Ahmed, I. A comprehensive characterisation of safflower oil for its potential applications as a bioactive food ingredient-A review. *Trends Food Sci. Technol.* **66**, 176-186 (2017). doi:10.1016/j.tifs.2017.06.009
5) Mihaela, P.; Josef, R.; Monica, N.; Rudolf, Z. Perspectives of safflower oil as biodiesel source for South Eastern Europe (comparative study: Safflower, soybean and rapeseed). *Fuel* **111**, 114-119 (2013). doi:10.1016/j.fuel.2013.04.012
6) Matthaus, B.; Özcan, M.M.; Al Juhaimi, F.Y. Fatty acid composition and tocopherol profiles of safflower (*Carthamus tinctorius* L.) seed oils. *Nat. Prod. Res.* **29**, 193-196 (2015). doi:10.1080/14786419.2014.971316.
7) Norris, L.E.; Collene, A.L.; Asp, M.L.; Hsu, J.C.; Liu, L.F. *et al.* Comparison of dietary conjugated linoleic acid with safflower oil on body composition in obese postmenopausal women with type 2 diabetes mellitus. *Am. J. Clin. Nutr.* **90**, 468-476 (2009). doi:10.3945/ajcn.2008.27371
8) Neschen, S.; Moore, I.; Regittnig, W.; Yu, C.L.; Wang, Y. *et al.* Contrasting effects of fish oil and safflower oil on hepatic peroxisomal and tissue lipid content. *Am. J.*

Physiol. Endocrinol. Metab. **282**, 395-401 (2002). doi:10.1152/ajpendo.00414.2001
9) Han, X.; Cheng, L.; Zhang, R.; Bi, J. Extraction of safflower seed oil by supercritical CO_2. *J. Food Eng.* **92**, 370-376 (2009). doi:10.1016/j.jfoodeng.2008.12.002
10) Ayadi, M.; Awad, S.; Villot, A.; Abderrabba, M.; Tazerout, M. Heterogeneous acid catalyst preparation from olive pomace and its use for olive pomace oil esterification. *Renew. Energ.* **165**, 1-13 (2021).
11) González-Rámila, S.; Mateos, R.; García-Cordero, J.; Seguido, M.A.; Bravo-Clemente, L.; Sarriá, B. Olive pomace oil versus high oleic sunflower oil and sunflower oil: A comparative study in healthy and cardiovascular risk humans. *Foods* **11**, 2186 (2022). doi:10.3390/foods11152186
12) Ruiz-Méndez, M.V.; Márquez-Ruiz, G.; Holgado, F.; Velasco, J. Stability of bioactive compounds in olive-pomace oil at frying temperature and incorporation into fried foods. *Foods* **10**, 2906 (2021). doi:10.3390/foods10122906
13) Mateos, R.; Sarria, B.; Bravo, L. Nutritional and other health properties of olive pomace oil. *Crit. Rev. Food Sci. Nutr.* **60**, 3506-3521 (2020). doi:10.1080/10408398.2019.1698005
14) AOCS. *Official and Recommended Practices of the American Oil Chemists' Society*. Champaign, IL (2003).
15) IUPAC. International Union of Pure and Applied Chemistry. *Standard Methods for Analysis of Oils, Fats and Derivates*, 7th ed., IUPAC Method 2.301, Blackwell Scientific Publications, Palo Alto, California, USA (1987).
16) DGF. *German Standard Methods for the Analysis of Fats and other Lipids*: C-VI 18 (10) A & B, Ester-bound 3-chloropropane-1,2-diol (3MCPDEsters) and glycidol (glycidyl esters): Determination in fats and oils by GC-MS, WVG (2009).
17) Cheng, W.; Liu, G.; Liu, X. Formation of glycidyl fatty acid esters both in real edible oils during laboratory-scale refining and in chemical model during high temperature exposure. *J. Agric. Food Chem.* **64**, 5919-5927 (2016). doi: 10.1021/acs.jafc.6b01520
18) Prabsangob, N.; Benjakul, S. Enhancement of thermal stability of soybean oil by blending with tea seed oil. *Emir. J. Food Agric.* **30**, 968-977 (2018). doi: 10.9755/ejfa.2018.v30.i11.1862
19) TFC. *Regulation on Special Hygiene Rules for Fats and Oils Used in Frying*. Turkish Food Codex, number: 28290 (2012).
20) Aşkın, B.; Kaya, Y. Effect of deep frying process on the quality of the refined oleic/linoleic sunflower seed oil and olive oil. *J. Food Sci. Technol.* **57**, 4716-4725 (2020). doi:10.1007/s13197-020-04655-4
21) Abdulkarim, S.M.; Long, K.; Lai, O.M.; Muhammad, S.K.S.; Ghazali, H.M. Frying quality and stability of high-oleic *Moringa oleifera* seed oil in comparison with other vegetable oils. *Food Chem.* **105**, 1382-1389 (2007). doi: 10.1016/j.foodchem.2007.05.013
22) Shahidi, F.; Wanasundara, U.N. Methods for measuring oxidative rancidity in fats and oils. in *Food lipids: Chemistry, nutrition and biotechnology* (Akoh, C.C.; Min, D.B. eds.), 2nd ed., Marcel Dekker, New York, pp. 465-482 (2002).
23) Mba, O.I.; Dumont, M.J.; Ngadi, M. Thermostability and degradation kinetics of tocochromanols and carotenoids in palm oil, canola oil and their blends during deep-fat frying. *LWT Food Sci. Technol.* **82**, 131-138 (2016). doi:10.1016/j.lwt.2017.04.027
24) Casal, S.; Malheiro, R.; Sendas, A.; Oliveira, B.P.; Pereira, J.A. Olive oil stability under deep-frying conditions. *Food Chem. Toxicol.* **48**, 2972-2979 (2010). doi:10.1016/j.fct.2010.07.036
25) Rodríguez, G.; Squeo, G.; Estivi, L.; Quezada Berru, S.; Buleje, D. *et al.* Changes in stability, tocopherols, fatty acids and antioxidant capacity of sacha inchi (Plukenetia volubilis) oil during French fries deep-frying. *Food Chem.* **340**, 127942 (2021). doi:10.1016/j.foodchem.2020.127942
26) Al-Khusaibi, M.; Gordon, M.H.; Lovegrove, J.A.; Niranjan, K. Frying of potato chips in a blend of canola oil and palm olein: changes in levels of individual fatty acids and tocols. *Int. J. Food Sci. Technol.* **47**, 1701-1709 (2012). doi: 10.1111/j.1365-2621.2012.03024.x
27) Ahmad, M.H.; Saeed, N.; Imran, M.; Kamran Khan, M.; Muhammad, N. *et al.* Rapid and nondestructive characterization of multiple frying sunflower oil blend using fourier transform infrared spectroscopy and chemometrics. *Int. J. Food Prop.* **25**, 214-226 (2022). doi: 10.1080/10942912.2022.2027442
28) Wang, S.N.; Sui, X.N.; Wang, Z.J.; Qi, B.K.; Jiang, L.Z. *et al.* Improvement in thermal stability of soybean oil by blending with camellia oil during deep fat frying. *Eur. J. Lipid Sci. Technol.* **118**, 524-531 (2016). doi: 10.1002/ejlt.201500085
29) Ben Hammouda, I.; Zribi, A.; Mansour, A.B.; Matthäus, B.; Bouaziz, M. Effect of deep-frying on 3-MCPD esters and glycidyl esters contents and quality control of refined olive pomace oil blended with refined palm oil. *Eur. Food Res. Technol.* **243**, 1219-1227 (2017). doi: 10.1007/s00217-016-2836-4
30) Pantzaris, T.P. Comparison of monounsaturated and polyunsaturated oils in continuous frying. *Grasas Aceites* **49**, 319-352 (1998). doi:10.3989/gya.1998.v49.i3-4.733
31) Li, X.; Li, J.; Wang, Y.; Cao, P.; Liu, Y. Effects of frying oils' fatty acids profile on the formation of polar lipids components and their retention in French fries over deep-frying process. *Food Chem.* **237**, 98-105 (2017).

doi:10.1016/j.foodchem.2017.05.100.
32) De Marco, E.; Savarese, M.; Parisini, C.; Battimo, I.; Falco, S.; Sacchi, R. Frying performance of a sunflower/palm oil blend in comparison with pure palm oil. *Eur. J. Lipid Sci. Technol.* **109**, 237-246(2007). doi: 10.1002/ejlt.200600192
33) Eryılmaz, T.; Cesur, C.; Yesilyurt, M.K.; Aydın, E. Aspir (*Carthamus tinctorius* L.), Remzibey-05 tohum yağı metil esteri: Potansiyel dizel motor uygulamaları için yakıt özellikleri. *Türk tarım doğa bilim. derg.* **1**(1), 85-90(2014).
34) Kaur, A.; Singh, B.; Kaur, A.; Yadav, M.P.; Singh, N. Impact of intermittent frying on chemical properties, fatty acid composition, and oxidative stability of 10 different vegetable oil blends. *J. Food Process. Preserv.* **45**, e16015(2021). doi:10.1111/jfpp.16015
35) Aladedunye, F.A.; Przybylski, R. Degradation and nutritional quality changes of oil during frying. *J. Am. Oil Chem. Soc.* **86**, 149-156(2009). doi: 10.1007/s11746-008-1328-5
36) Goh, K.M.; Wong, Y.H.; Tan, C.P.; Nyam, K.L. A summary of 2-, 3-MCPD esters and glycidyl ester occurrence during frying and baking processes. *Curr. Res. Food Sci.* **4**, 460-469(2021). doi:10.1016/j.crfs.2021.07.002
37) Wong, Y.H.; Muhamad, H.; Abas, F.; Lai, O.M.; Nyam, K.L.; Tan, C.P. Effects of temperature and NaCl on the formation of 3-MCPD esters and glycidyl esters in refined, bleached and deodorized palm olein during deep-fat frying of potato chips. *Food Chem.* **219**, 126-130(2017). doi: 10.1016/j.foodchem.2016.09.130
38) Xu, L.; Zhang, Y.; Gong, M.; Huang, J.; Jin, Q. *et al.* Change of fatty acid esters of MCPD and glycidol during restaurant deep frying of fish nuggets and their correlations with total polar compounds. *Int. J. Food Sci. Technol.* **55**, 2794-2801(2020). doi:10.1111/ijfs.14532
39) Aniołowska, M.; Kita, A. The effect of type of oil and degree of degradation on glycidyl Esters content during the frying of French fries. *J. Am. Oil Chem. Soc.* **92**, 1621-1631(2015). doi:10.1007/s11746-015-2715-3
40) Dingel, A.; Matissek, R. Esters of 3-monochloropropane-1,2-diol and glycidol: No formation by deep frying during large-scale production of potato crisps. *Eur. Food Res. Technol.* **241**, 719-723(2015). doi:10.1007/s00217-015-2491-1

CC BY 4.0(Attribution 4.0 International). This license allows users to share and adapt an article, even commercially, as long as appropriate credit is given. That is, this license lets others copy, distribute, remix, and build upon the Article, even commercially, provided the original source and Authors are credited.