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Utilization of Mango Kernel Seed For Improving The Oxidative Stability of Sun-Flower Oil During Frying Process

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ABSTRACT

This study investigated the potential of mango kernel oil (MKO) and phenolic extracts from defatted mango kernel seeds (DMKS) as natural antioxidants to improve the oxidative stability of sunflower oil (SFO) during frying. Proximate analysis showed that mango kernels are rich in carbohydrates (74.21%) and contain appreciable levels of fat (13.36%) and protein (6.43%). MKO was characterized by high levels of oleic (43.89%) and stearic acids (39.18%), while DMKS extract exhibited a higher phenolic content (3960.32mg caffeic/100g) than MKO (1356.7mg caffeic/100g). High-performance liquid chromatography identified several phenolic compounds, including gallic acid, pyrogallol, catechol, and catechin. Oxidative stability tests revealed that blending SFO with MKO and phenolic extract significantly extended the induction period compared to pure SFO and even to synthetic antioxidant (TBHQ). During frying of potato fingers, the blends reduced peroxide value, free fatty acids, polymer content, and oxidized fatty acids, while maintaining more favorable viscosity and refractive index values. The most effective treatment was the combination of 85% SFO+ 15% MKO+400ppm phenolic extract, which provided superior stability throughout the frying period. These findings highlight mango kernel by-products as promising natural antioxidants that could serve as healthier and more sustainable alternatives to synthetic additives in frying oils.

1. Introduction

Mango (*Mangifera indica L.*) is among the most widely consumed tropical fruits, produced both fresh and processed into juice, pulp, jam, puree, and other products. Global mango production exceeds 52 million tons annually (FAO, 2019). However, processing generates large amounts of by-products, mainly seeds and peels, which account for 35–60% of fruit weight and are often discarded, causing environmental problems (Larrauri et al., 1996; Rojas et al., 2020). These residues are rich in bioactive compounds such as phenolics, vitamins, and tocopherols, with pharmacological attributes including antioxidant, antimicrobial, anti-inflammatory, and anticancer effects (Ribeiro et al., 2008; Sumaya-Martínez et al., 2019; Castro-Vargas et al., 2019). Mango seeds are an important by-product of industrial processing. The kernel constitutes 45–85% of the seed and about 20% of the fruit weight (Solís-Fuentes & Duran-de-Bazúa, 2004). Mango kernel seed (MKS) contains 12–15% oil, rich in fatty acids with nutritional and functional significance (Jahurul et al., 2015). Mango kernel oil (MKO) typically contains high proportions of oleic acid (45%) and stearic acid (38%) (Nzikou et al., 2010). Oleic acid, a monounsaturated fatty acid, reduces triglycerides, LDL-cholesterol, and total cholesterol, and contributes to oxidative stability (Abdulkarim et al., 2007). Stearic acid, a saturated fatty acid, is associated with functional and structural roles in biomolecules (Netravali, 2003). Thus, the predominance of oleic and stearic acids, along with tocopherols, carotenoids, and phenolic compounds, enhances the oxidative stability of MKO (Abdel-Razik et al., 2012). Polyphenols from mango kernels represent a valuable natural antioxidant source.

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These compounds include mangiferin, gallic acid, catechin, and others, which have demonstrated cardio- and hepatoprotective, anticancer, and anti-ageing effects (Mohdaly et al., 2011; Jafari et al., 2014; Castro-Vargas et al., 2019). Their recovery provides an opportunity for waste valorization, offering both health-promoting properties and economic benefits while reducing environmental burdens (Ballesteros-Vivas et al., 2019; Ordoñez-Torres et al., 2021; Shirahigue & Ceccato-Antonini, 2020). Deep-fat frying is one of the most common cooking methods, involving immersion of food in hot oil at 150–190 °C. During frying, oils are exposed to high temperature, oxygen, and food moisture, leading to hydrolysis, oxidation, and polymerization reactions (Choe & Min, 2007; Katragadda et al., 2010). These reactions produce undesirable flavors, odors, and discoloration, negatively affecting the nutritional and sensory quality of oils and fried foods (Izaki et al., 1984; Jacobson, 1991). The rate of deterioration depends on frying conditions, food-to-oil ratio, oil composition, and the presence of antioxidants (Choe & Min, 2007). To minimize degradation, synthetic antioxidants such as butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), and tert-butylhydroquinone (TBHQ) are commonly used (Choe & Min, 2009). However, their safety has been questioned due to possible carcinogenicity and toxicological concerns (Samotyja & Małecka, 2010; Zhang et al., 2010). Several countries, including Japan and members of the European Union, have restricted or banned their use (Wanasundara & Shahidi, 1998; Tang et al., 2001). These concerns have stimulated growing interest in natural antioxidants derived from plant sources for food preservation (Dai & Mumper, 2010). Considering the high oxidative stability of MKO and the strong antioxidant activity of mango kernel phenolic compounds, the present research was conducted to evaluate the effectiveness of MKO and phenolic extracts from defatted mango kernel seeds as natural alternatives to synthetic antioxidants. The study focused on improving the oxidative stability of sunflower oil during deep-fat frying.

2. Materials and methods

Materials

Mango seeds were obtained from Kaha Company for preserved food El-Qalubiya Governorate, Egypt. Potatoes were purchased from a local market, El-Qalubiya. while refined sunflower oil (free from antioxidants) was provided by Arma Company for Food Industries (10th of Ramadan, Egypt). All Chemicals and solvents of analytical grade were purchased from El-Gomhouriya Company for Chemicals and Drugs (Cairo, Egypt).

Methods

MKS powder preparation

Mango seeds were washed, air dried, and manually separated, to obtain the kernels. The kernels were cut into small pieces, dried 50°C overnight. ground using Mikro-Feinmühle-Culatti mill (JKA-Co 7813 Staufen) and sieved to obtain fine powder (Abdalla et al., 2007).

Extraction of MKO

Oil was extracted by soaking dried kernel powder in hexane (2:1, v/w) with gentle stirring for 24 h, The mixture was filtered and the solvent was removed under vacuum using a rotary evaporator. The process was repeated for three times. The extracted oil was stored in brown bottles at −20°C until use.

Extraction of phenolic compounds from MKO

Phenolics were extracted from 5g of MKO dissolved in 50ml hexane using 30 ml water/ethanol (10:90, v/v). The process was repeated three times, and the combined extracts were evaporated to dryness under vacuum. The residue was dissolved in 1ml ethanol (Gutfinger, 1981, with modifications).

Extraction of phenolic compounds from DMKS

Defatted kernel powder (5g) was shaken overnight in 50 ml absolute ethanol in the dark, then filtered. The solvent was evaporated under reduced pressure at 30°C. The extraction was repeated three times, and the final volume was adjusted to 100 ml with ethanol (Sigdel et al., 2018).

Determination of total phenolic content

The total phenolic content of MKO or DMKS extracts was measured using the Folin–Ciocalteu reagent and results were expressed as mg of caffeic acid equivalents per 100g sample (Gutfinger, 1981).

Oil blends were prepared at 35°C as follow:

(A) 100% SFO, (B) 100% SFO+200ppm TBHQ
(C)100% SFO+200ppm phenolic extract of DMKS
(D) 100% SFO+400ppm phenolic extract of DMKS
(E)100% SFO+600ppm phenolic extract of DMKS
(F) 90% SFO+10% MKO
(G) 85% SFO+15% MKO
(H) 80% SFO+20% MKO
(I) 85%SFO+15% MKO+400ppm phenolic extract of DMKS

Oxidative stability

The oxidative stability of oil blends was evaluated using a Rancimat 679 apparatus (Metrohm, Switzerland). Five grams of oil were heated to 100±2°C with an airflow of 20L/h. Induction time (h) was recorded (Gutierrez et al., 1988).

Frying process

Four blends were selected for frying experiments based on oxidative stability: (B) SFO+200ppm TBHQ, (E) SFO+600ppm phenolic extract, (G) 85% SFO+15% MKO, and (I) 85% SFO+15% MKO + 400 ppm phenolic extract. For each treatment, 3 kg of oil were used to fry potato fingers (1×1×4cm) at 180±5° C in a domestic fryer (Tefal, France) for 25h (5 h daily for 5 days). Oil samples (50ml) were withdrawn at the end of each day, cooled, and stored at −18°C for analysis.

Determination of proximate analysis of MKS

Moisture, total lipids, protein, ash, and fibers were determined according to AOAC (2019). Total carbohydrate content was calculated according to Ranganna (2004) by difference as in the following equation:

Carbohydrate (% dry basis) = 100- (crude protein + total ash + crude fiber + crude fat)

Determination of some physico-chemical properties of oils

Refractive index (RI), melting point, free fatty acids (FFA% as oleic acid) and peroxide value (PV), saponification value (SV), iodine value (IV), unsaponifiable matter percentage and color (Lovibond Tintometer Model F, 5.25- inch cell) were determined according to AOAC (2019).

Determination of viscosity

Viscosity (cp) was determined using a Brookfield RVDV Viscometer with spindle SC4-21 at 25°C (SFO) and 40°C (MKO) (Howard, 1991).

Polymer content

Polymer content was determined according to Wu & Nawar (1986).

Total polar compounds

Total polar compounds were measured by column chromatography (Waltking & Wessels, 1981).

Oxidized fatty acids content

Petroleum ether-insoluble oxidized fatty acids were determined according to Billek et al. (1978).

Identification of the fatty acids profile

Fatty acids methyl esters were prepared MKO according to the method of ISO12966-2(2017) followed by the identification of methyl esters using an Agilent 6890 series Gas Chromatography apparatus equipped with a DB-23 (60m×0.32×25µm). Nitrogen was used as the carrier gas at a flow rate of 1.5ml/min, splitting ratio of 1:50. The injector temperature was set at 250° C, and the Flame Ionization Detector (FID) temperature was 280°C. The temperature setting was as follows: 150°C to 210°C at 5°C/min, followed by a hold at 210°C for 25 minutes. Peaks were identified by comparing retention times with standard methyl esters.

Identification and determination of phenolic compounds

Phenolic compounds of MKO and DMKS were identified and determined using high performance liquid chromatography (HPLC) following the method described by Goupy et al. (1999). The HPLC Hewllet Packared (series 1050) equipped with autosamplling injector, solvent degasser, ultraviolet (UV) detector set at 280nm and quaternary HP pump (series 1100). The column temperature was maintained at 35°C. Gradient separation was carried out with methanol and acetonitrile as a mobile phase at flow rate of 1ml. Phenolic acids standards were dissolved in a mobile phase and injected into HPLC. Retention time and peak area were used to calculation of phenolic compounds concentrations by the data analysis of HEWLLET Packared software.

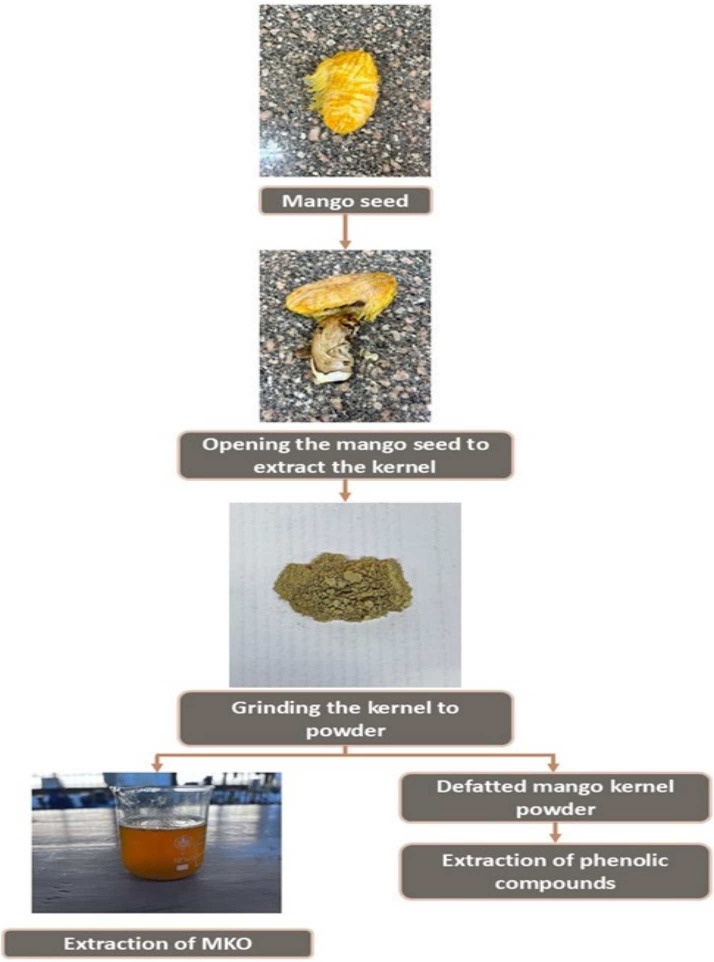

Figure 1. Separation of mango kernel from the seed, drying and grinding, extraction of MKO and phenolic compounds

Statistical Analysis

The experiment was conducted in a completely randomized design with three replicates. Data were expressed as mean±SD, and significant differences among treatments were determined using Duncan's multiple range test at $P \leq 0.05$ (Steel et al., 1997).

3. Results and Discussion

Results in Table 1 showed that MKS contained 42.31% moisture. This result was in parallel to that was reported by Nzikou et al. (2010). Also, it contained 13.36% fat, 6.43% crude protein, 3.60% ash, 2.40% crude fibers, 74.21% total carbohydrate by difference. These results are in agreement with Ojha et al. (2019). Our results showed higher fat content than those obtained by Zahoor et al. (2023). This difference in oil percentage may be due to the differences in variety of plant, cultivation climate, ripening stage, harvesting time or extraction method.

Table 1. Proximate analysis of Mango Kernel Seed (MKS) on dry basis

Characteristics	Percentage (%)
Moisture content	42.31 %
Fat content	13.36 %
Crude protein	6.43 %
Ash content	3.60 %
Crude fiber	2.40 %
Total carbohydrate (by difference)	74.21 %

The physicochemical properties of mango kernel oil (MKO) and sunflower oil (SFO) are presented in Table 2.

Refractive index (RI)

MKO exhibited a lower RI (1.4570) than SFO (1.4722). This difference reflects the lower unsaturation level in MKO and corresponds with the findings of Diomande et al. (2021) and Zahoor et al. (2023), who demonstrated that oils richer in saturated fatty acids generally have lower refractive indices.

Viscosity

The viscosity of MKO (65cp at 40°C) was higher than that of SFO (49.0cp at 25°C). Oil viscosity is strongly affected by the degree of unsaturation and molecular size of fatty acids. As reported by Abramović & Klofutar (1998), the presence of cis double bonds introduces bends in the hydrocarbon chain, preventing close molecular packing and thereby reducing viscosity. Consequently, oils rich in polyunsaturated fatty acids exhibit lower viscosity due to their less rigid structure and higher fluidity. In contrast, a higher proportion of saturated fatty acids contributes to stronger molecular interactions and higher resistance to flow. Ennouri et al. (2005) confirmed that increased saturation, particularly from smaller fatty acids such as palmitic acid, leads to an increase in oil viscosity. The elevated viscosity of MKO can therefore be attributed to its high content of saturated and monounsaturated fatty acids, mainly stearic and oleic acids.

Color

Lovibond color values showed that MKO (5.6R + 30Y) was darker than SFO (1.8R+16Y) (Table 2). Esraa et al. (2024) reported even higher color intensity for MKO (10R+30Y), while Nadeem et al. (2017) found comparable values (1.7R+17Y). These variations may be attributed to differences in mango varieties, maturity stage, and extraction methods. Also, MKO was not exposed to refining process as in SFO. The darker color of MKO is characteristic and does not negatively affect its functional properties.

Melting point

As shown in Table 2, the melting point of MKO was 34°C, which is relatively high compared with most vegetable oils. This property is attributed to the high proportion of saturated fatty acids, particularly stearic acid, present in MKO. The results were consistent with Abdel-Razik et al. (2012), who also reported elevated melting points for mango kernel oil due to its fatty acid composition.

Iodine value

As presented in Table 2, MKO showed a lower iodine value (56.72g I_2/100g oil) compared with SFO (118.9g I_2/100g oil). This difference is attributed to the higher proportion of unsaturated fatty acids in SFO, since the iodine value is a direct measure of the degree of unsaturation in oils and is commonly used to assess oxidative stability in industrial applications (Xu et al., 2007). The present results are consistent with Esraa et al. (2024), who reported a similar iodine value for MKO (54.25g I_2/100g oil).

Saponification value

The saponification value is an important parameter used to estimate the average molecular weight or chain length of fatty acids present in triacylglycerols. As shown in Table 2., the saponification values of MKO and SFO were 183.9 and 195.61 mg KOH/g oil, respectively. The relatively lower value of MKO reflects the predominance of longer-chain fatty acids in its triacylglycerols. These results are consistent with the findings of Esraa et al. (2024), who reported a saponification value of 189.36mg KOH/g oil for MKO.

Unsaponifiable matter

Unsaponifiable matter is component of an oily mixture which fails to form soap when blended with NaOH. The composition of unsaponifiable matter of vegetable oils including tocopherols, sterols and squalene is of great importance for oil characteristics and stability (Sims et al., 1972). Our results in Table 2 revealed that the percentage of unsaponifiable matter in SFO (0.53%) was less than that of MKO (2.4%). Zahoor et al. (2023) explained that the unsaponifiable matter of MKO ranged from 1.20 to 3.30%.

FFA% & PV

Free fatty acids (FFA) and peroxide value (PV) are widely recognized as key indices of oil quality. As shown in Table 2, MKO contained 0.36% FFA and 0.10 meq O_2/kg oil, while SFO contained 0.05% FFA and 2.07 meq O_2/kg oil. The low FFA and PV values of MKO, despite being unrefined, indicate that the mango seed oil was almost free from hydrolytic rancidity, which typically results from lipase activity. This suggests that MKO could be directly utilized in industrial applications without the need for further neutralization, as previously described by Arogba (1997). Furthermore, the exceptionally low PV confirms the high quality of MKO and highlights its potential use in improving the oxidative stability of less stable vegetable oils.

Table 2. Physical and chemical properties of Mango kernel seed oil and sunflower oil

Properties	Mango seed kernel oil (MKO)	Sunflower oil (SFO)
Refractive index (RI)	1.4570(at 40°C)	1.4722 (at 25°C)
Viscosity (CP)	65cp	49.00cp
Melting point	34ºC	ND
Color	5.6R+30Y	1.8R+16Y
Free fatty acids (FFA)% as oleic acid	0.36	0.05
Peroxide value (PV) (meq. O_2/Kg oil)	0.10	2.07
Iodine value (gI_2/100g oil)	56.72	118.9
Saponification value (mg KOH/g oil)	183.9	195.61
Unsaponifiable matter (%)	2.4	0.53

-ND: Not determined

Fatty acid composition

It is commonly recognized that understanding vegetable oil's fatty acid composition can help predict its potential uses for edible or industrial products, and relate potential oxidation to particular unsaturated fatty acids. Additionally, the oxidative stability, and safe, healthy quality of these lipids are all significantly connected with the fatty acid content of dietary oils and fats (Mustafa et al., 2023). The fatty acid composition of MKO, SFO, and their blends is shown in Table 3. Analysis by gas chromatography revealed that the major fatty acid in MKO was oleic acid (43.89%), followed by stearic acid (39.18%). The total saturated fatty acids accounted for 50.66%, giving an unsaturated-to-saturated ratio of 0.98, which indicates high oxidative stability. Similar findings were reported by Hemavathy et al. (1987) and confirmed by Esraa et al. (2024). Notably, MKO was free from trans fatty acids, further emphasizing its nutritional quality. In contrast, SFO was characterized by a high proportion of linoleic acid (60.98%) and oleic acid (26.71%), with a total unsaturated fatty acid content of 88.54%, much higher than that in MKO. This composition explains the lower oxidative stability of SFO compared with MKO. Blending MKO with SFO improved the fatty acid profile of SFO by increasing oleic and stearic acid contents, raising the proportion of saturated fatty acids, and lowering the unsaturated-to-saturated ratio. These changes suggest that MKO could enhance the oxidative stability of SFO when used in blends.

Table 3. Fatty acids composition of MKO, sunflower oil and their blends

Fatty acids	MKO	SFO	SFO +10%MKO	SFO+15% MKO	SFO+20%MKO
$C_{14:0}$	ND	0.11	0.10	0.09	0.09
$C_{16:0}$	8.21	7.75	7.80	7.82	7.84
$C_{16:1}$	0.08	0.14	0.13	0.13	0.13
$C_{17:0}$	0.15	0.03	0.04	0.05	0.05
$C_{17:1}$	0.03	0.03	0.03	0.03	0.03
$C_{18:0}$	39.18	3.05	6.66	8.47	10.28
$C_{18:1}$	43.89	26.71	28.43	29.29	30.15
$C_{18:2T}$	ND	0.51	0.46	0.43	0.41
$C_{18:2}$	5.08	60.98	55.44	52.60	49.8
$C_{18:3}$	0.10	0.06	0.06	0.07	0.07
$C_{20:0}$	2.60	0.16	0.40	0.53	0.65
$C_{20:1}$	0.16	0.11	0.12	0.12	0.12
$C_{22:0}$	0.52	0.36	0.37	0.38	0.39
TSFA	50.66	11.46	15.37	17.34	19.30
TUSFA	49.34	88.54	84.63	82.66	80.70
TUSFA/TSFA	0.98	7.70	5.51	4.76	4.18

-TSFA: Total saturated fatty acids, -TUSFA: Total unsaturated fatty acids, -ND: Not detected

Phenolic compounds

Phenolic compounds are recognized as major natural antioxidants due to their high phytochemical content and strong antioxidant capacity (Dimitrios, 2006). In addition, they have been associated with potential therapeutic effects in chronic diseases such as diabetes, hypertension, and dyslipidemia (Dai & Mumper, 2010).

The phenolic profile of mango kernel seed extract (MKSE) and mango kernel oil (MKO) was determined using HPLC (Table 4). Twelve compounds were identified in MKSE and eleven in MKO. Pyrogallol was the predominant compound in both MKSE and MKO, followed by gallic acid, chlorogenic acid, catechol, and catechin, whereas p-hydroxybenzoic acid and caffeine were detected at lower levels. Overall, all phenolic compounds were present at higher concentrations in MKSE compared with MKO. These phenolic compounds have been reported to exert several biological activities. For instance, gallic and ellagic acids are known for their antibacterial, antioxidant, anticancer, antiviral, anti-allergic, and anti-inflammatory properties (Soong & Barlow, 2006). Gallic acid also shows potential in the prevention of cardiovascular and metabolic disorders (Keyvani-Ghamsari et al., 2023). Furthermore, Zein et al. (2005) reported that catechin mixtures from MKO at 1% concentration exhibited stronger antioxidant activity than 200 ppm of BHT, confirming the high antioxidant capacity of mango seed phenolics. Quantitatively, MKSE contained higher total phenolic compounds (3960.32mg caffeic acid/100g) than MKO (1356.7mg caffeic acid/100g). These values were lower than those reported by Mutua et al. (2017), who found phenolic contents ranging from 68.71 to 72.05mg GAE/g in four mango varieties. Such variability in phenolic values has been attributed to differences in cultivar, fruit maturity, climatic conditions, and extraction methods (Muñoz et al., 2013). Based on its phenolic composition and antioxidant potential, MKO has been suggested as a promising natural antioxidant for retarding lipid oxidation in edible oils (Abdel-Razik, et al. 2012). This highlights mango seed as a valuable by-product that can be exploited in food systems to extend the shelf life of less stable vegetable oils.

Table 4. Total phenolic content and identification of phenolic compounds in defatted mango seeds extract and MKO by HPLC

Compound	DMKS (mg caffeic acid /100g)	MKO (mg caffeic acid/100g)
Gallic acid	325.10	128.30
Catechin	259.15	43.89
Protocatechuic acid	177.05	23.45
Pyrogallol	576.03	132.81
Cinnamic acid	93.95	13.74
Caffeic acid	134.50	27.23
Caffeine	55.23	17.11
Chlorogenic acid	306.16	128.7
Catechol	275.05	96.23
P-Coumaric acid	67.51	32.12
P-OH benzoic	38.18	ND
Salicylic acid	135.91	37.00
Total phenolic compounds	3960.32	1356.7

Oxidative stability

The oxidative stability of MKO, SFO, and their blends at 100°C was evaluated using the Rancimat method, are represented in Table 5. MKO exhibited a significantly higher induction period (108.4h) compared with SFO (7.3h), confirming its superior resistance to oxidation. This high stability can be attributed to the high proportion of saturated fatty acids, particularly stearic acid, and monounsaturated fatty acid (oleic acid). Conversely, while PUFA-rich oils like sunflower oil are prone to oxidation due to their high linoleic acid content, MUFA-rich oils exhibit greater stability. As well as the presence of natural antioxidants such as tocopherols and phenolic compounds. These findings agree with Hemavathy et al. (1987) and Abdel-Razik et al. (2012), who also reported that MKO to play an important role in protecting the human body and to be used as mixtures with less stable oils for cooking and frying. Blending MKO with SFO markedly improved the oxidative stability of SFO. The induction period of SFO increased proportionally with the level of MKO substitution, demonstrating the effectiveness of MKO in enhancing frying oil quality.

Similarly, the addition of mango kernel seed extract (MKSE) further extended the induction periods of SFO, especially at concentrations of 400 and 600 ppm, reflecting the strong antioxidant activity of the phenolic compounds. These results are consistent with the findings of Zein et al. (2005), who demonstrated that phenolic extracts from mango kernel exhibited greater antioxidant activity than synthetic antioxidants such as BHT. Our study revealed that combining phenolic extract with MKO had a more pronounced impact on enhancing the oxidative stability of sunflower oil compared to using either additive alone. Overall, the Rancimat data confirm that MKO and its extracts can be effectively utilized to improve the oxidative stability of less stable vegetable oils, thereby reducing reliance on synthetic antioxidants and extending the shelf life of edible oils.

Table 5. Oxidative stability of MKO, sunflower oil and its different blends with phenolic extract of defatted mango kernel or MKO

Oils and blends	Induction period (h) at 100°C
MKO	108.4
SFO without antioxidant	7.3
SFO+200ppm TBHQ	12.54
SFO+200ppm phenolic extract	10.92
SFO+400ppm phenolic extract	12.97
SFO+600ppm phenolic extract	15.95
SFO+10% MKO	10.13
SFO+15% MKO	11.85
SFO+20% MKO	13.50
85% SFO+15% MKO+400ppm phenolic extract	19.71

Changes in Physical and Chemical Characteristics During Frying

Table 6 presents the changes in refractive index (RI), viscosity, free fatty acids (FFA)%, and peroxide value (PV) of SFO and its blends with MKO during the frying process. It is well established that deep frying alters the physical and chemical characteristics of oils, leading to decrease the unsaturated fatty acids and increased viscosity, color, density, foaming, and accumulation of free fatty acids and polymeric compounds (Choe & Min, 2007).

Refractive Index (RI)

The RI of SFO increased progressively with frying time across all treatments. This increase is associated with the formation of conjugated double bonds from polyunsaturated fatty acids under thermal stress (Ali & El-Anany, 2014). Similar trends were reported by Hashem et al. (2017) and Ghaly & El-Khamissi (2021). Treatments containing 15% MKO, particularly when combined with 400 ppm phenolic extract, exhibited the lowest RI values, which may be attributed to the fatty acid composition of MKO (Table 3). No significant differences were observed between oils treated with 600ppm phenolic extract DMKS and those containing 200ppm TBHQ.

Viscosity

Viscosity, an indicator of oil resistance to flow and an indirect measure of polymeric compound formation, increased gradually in all samples during frying. Blends containing MKO initially exhibited higher viscosity than pure SFO due to the naturally higher viscosity of MKO, which results from its high saturated fatty acid content. However, the rate of viscosity increase during frying was lower in MKO-containing blends, reflecting the greater oxidative stability of MKO. At the end of frying, the lowest viscosity (68.50cp) was recorded for the treatment of 85% SFO+15% MKO+400 ppm phenolic extract. There is no significant difference recorded between SFO+600 ppm phenolic extract and SFO+200ppm TBHQ. These results are in line with Hashem et al. (2017), who reported a significant increase in oil viscosity during repeated frying.

Free Fatty Acids (FFA)

FFA levels increased gradually during frying in all treatments due to hydrolysis of triglycerides when exposed to air, moisture, and high temperature, consistent with previous studies (Chung et al., 2004 and Horuz & Maskan, 2015). FFAs are more susceptible to thermal oxidation and resulting in polar molecules, unpleasant flavors and odors especially in oils with short-chain and unsaturated fatty acids due to their high-water solubility (Choe & Min, 2007). The lowest rate of increase was observed in 85% SFO+15% MKO+400 ppm phenolic extract, followed by SFO supplemented with 600 ppm phenolic extract. No significant differences were recorded between 85% SFO +15% MKO and SFO+200ppm TBHQ across the frying periods. These results are consistent with those of

Abdalla et al. (2007). and Hashem et al. (2017).

Peroxide Value (PV)

PV, an indicator of primary lipid oxidation (Suri et al., 2019), increased significantly with frying time in all samples. However, the sharpest increase was observed in SFO+TBHQ, while the slowest increase occurred in 85% SFO+15% MKO+400ppm phenolic extract. Oils containing 600ppm phenolic extract showed comparable oxidative stability to those treated with 200ppm TBHQ, particularly after 15–25 hours of frying. The inclusion of MKO also reduced PV values relative to pure SFO, likely due to the inherently lower PV of MKO (Table 2). These findings are in agreement with Abdalla et al. (2007), who reported that mango seed kernel extract effectively reduced peroxide and anisidine values, delaying oxidative rancidity and extending sunflower oil shelf life.

Table 6. Changes in physical (Refractive index and Viscosity) and some chemical characteristics (Refractive index, FFA%, and PV) of SFO and its different blends during frying process

Sample No.	Frying time (h)	Refractive index	Viscosity (cp)	FFA%	PV (meq. O_2/Kg oil)
B (SFO+200ppm TBHQ)	0	1.4722^{f}±0.0001	49.00^{k}±0.50	0.05^{k}±0.01	2.07^{q}±0.11
	5	1.4724^{f}±0.0001	51.00^{j}±0.44	0.20^{i}±0.02	4.47^{n}±0.12
	10	1.4727^{e}±0.0001	54.00^{hi}±1.00	0.48^{fg}±0.02	10.46^{k}±0.15
	15	1.4730^{d}±0.0	60.00^{f}±0.50	0.62^{e}±0.01	15.90^{f}±0.03
	20	1.4732^{bc}±0.0001	66.50^{d}±1.50	0.93^{c}±0.03	17.07^{d}±0.15
	25	1.4734^{ab}±0.0001	74.33^{a}±2.08	1.23^{a}±0.02	21.98^{a}±0.20
E (SFO+600ppm phenolic extract)	0	1.4722^{f}±0.0001	49.00^{k}±2.00	0.05^{k}±0.01	2.10^{q}±0.10
	5	1.4724^{f}±0.0001	50.66^{jk}±1.15	0.15^{ij}±0.01	4.31^{n}±0.05
	10	1.4726^{e}±0.0001	53.83^{hi}±1.04	0.41^{gh}±0.01	9.90^{i}±0.10
	15	1.4731^{cd}±0.0001	59.33^{f}±0.58	0.55^{ef}±0.02	15.13^{h}±0.03
	20	1.4732^{bc}±0.0	67.00^{cd}±1.04	0.89^{c}±0.01	16.85^{e}±0.06
	25	1.4735^{a}±0.0	73.00^{a}±1.73	1.10^{b}±0.10	19.92^{b}±0.02
G (85%SFO+ 15% MKO)	0	1.4694^{j}±0.0001	51.00^{j}±1.00	0.07^{k}±0.01	1.72^{r}±0.01
	5	1.4695^{ij}±0.0	52.33^{ij}±0.76	0.21^{i}±0.00	3.80^{o}±0.16
	10	1.4697^{ghi}±0.0001	54.40^{h}±0.72	0.49^{f}±0.02	9.72^{i}±0.02
	15	1.4697^{ghi}±0.0001	59.00^{fg}±0.87	0.60^{e}±0.02	15.60^{g}±0.17
	20	1.4699^{g}±0.0	63.66^{e}±1.52	0.94^{c}±0.02	17.60^{c}±0.04
	25	1.4699^{g}±0.0	70.33^{b}±0.29	1.21^{a}±0.02	21.96^{a}±0.11
I (85%SFO+ 15% MKO+ 400ppm phenolic extract)	0	1.4694^{j}±0.0001	51.00^{j}±0.60	0.07^{k}±0.00	1.72^{r}±0.02
	5	1.4695^{ij}±0.0	52.00^{j}±0.50	0.11^{jk}±0.01	3.03^{p}±0.11
	10	1.4695^{ij}±0.0	54.00^{hi}±1.00	0.35^{h}±0.01	6.70^{m}±0.20
	15	1.4696^{hij}±0.0001	57.50^{g}±0.50	0.50^{f}±0.02	10.90^{j}±0.17
	20	1.4697^{ghi}±0.0001	62.06^{e}±0.80	0.77^{d}±0.01	13.91^{i}±0.19
	25	1.4698^{gh}±0.0001	68.50^{c}±1.20	0.94^{c}±0.00	16.01^{f}±0.10
LSD 0.05		0.000191528914	1.7392173594	0.07220992042	0.18457202002

- Values are the mean of triplicate ± standard division, -Means, within the same column followed by the same letter have no significant difference

Data in Table 7. represent changes in polar, polymer, and oxidized fatty acids of SFO and its different blends with MKO.

Polar Compounds

The formation of polar compounds is directly related to primary and secondary oxidation processes occurring during frying. As peroxides and hydroperoxides decompose, short-chain acids, aldehydes, ketones, alcohols, and non-volatile products accumulate, leading to an increase in oil polarity (Xu et al., 1999 and Debnath et al., 2012). Data in Table 7. show that the percentage of polar compounds increased progressively with frying cycles, consistent with earlier studies (Romero et al., 2006; Wang et al., 2013 and Karakaya & Simsek, 2010). No significant differences were observed between 85% SFO+15% MKO and SFO+200ppm TBHQ at the same frying periods. However, SFO supplemented with 600 ppm phenolic extract had significantly lower polar content compared with SFO+200ppm TBHQ after 15–25h of frying. The most effective treatment was 85% SFO + 15% MKO+400 ppm phenolic extract, which exhibited the lowest polar compound levels throughout the frying process.

Polymer Compounds

Polymeric compounds such as dimers, trimers, and tetramers are generated during frying and contribute to undesirable changes in oil quality, including increased viscosity, refractive index, develop undesirable color in the food, bitter taste, foaming tendency, higher oil absorption by fried foods and reduce the heat transfer (Wang et al., 2016 and Tseng et al., 1996). Table 7. indicates a gradual increase in polymer content across all treatments with prolonged frying, in agreement with previous findings (Adel et al., 2015; Hashem et al., 2017; Ghaly & El-Khamissi, 2021). Oils containing MKO and its phenolic extract showed significantly lower polymer content compared with SFO+200ppm TBHQ. The greatest reduction was observed in 85% SFO+15% MKO+400 ppm phenolic extract, confirming the protective role of MKO and its antioxidants in limiting polymer formation.

Oxidized Fatty Acids (OFA%)

Oxidation during frying leads to the formation of degradation products such as oxidized fatty acids, including monoepoxy and oxo (keto) fatty acids (Warner, 2002). At the beginning of frying, no significant differences in OFA% were detected among treatments (Table 7). With continued frying, OFA% increased significantly in all samples, with the lowest increase recorded for 85% SFO+15% MKO+400 ppm phenolic extract, followed by 85% SFO+15% MKO. No significant differences were observed between SFO+600 ppm phenolic extract and SFO+200 ppm TBHQ at the end of frying. The lower OFA% in MKO-containing blends may be attributed to the distinctive fatty acid structure of MKO, which increases the proportion of total saturated fatty acids. Overall, the improved frying stability of SFO blended with MKO and enriched with MKSE can be explained by the higher thermal stability of polyphenolic antioxidants compared with synthetic antioxidants such as BHT, BHA, and TBHQ, which tend to degrade or volatilize during frying (Aladedunye & Matthäus, 2014).

Table 7. Changes in some chemical characteristics (Polar, Polymer, and Oxidized fatty acids) SFO and its different blends during frying process

Sample No.	Frying time (h)	Polar content (%)	Polymer content (%)	Oxidized fatty Acids (%)
B (SFO+200ppm TBHQ)	0	00.70^{n}±0.1	0.06^{o}±0.01	0.143^{o}±0.005
	5	04.41^{l}±0.41	0.9^{m} ±0.17	0.246^{lm}±0.015
	10	10.07^{j}±0.45	1.75^{k}±0.13	0.41^{j}±0.017
	15	14.36^{g}±0.58	2.82 ^{h}±0.09	0.52^{g}±0.017
	20	18.66^{d}±0.49	4.9^{e}±0.20	0.65^{d}±0.016
	25	23.06^{a}±0.25	7.91^{a}±0.13	0.93^{a}±0.02
E (SFO+600ppm phenolic extract)	0	00.70^{n}±0.10	0.06^{o}±0.01	0.143^{o}±0.006
	5	04.20^{l}±0.17	0.75^{mn}±0.05	0.20^{n}±0.01
	10	09.50^{j}±0.39	1.19^{l}±0.10	0.37^{k}±0.014
	15	13.51^{h}±0.55	2.49^{i}±0.07	0.49^{h}±0.01
	20	17.11^{e}±0.74	4.25^{f}±0.26	0.61^{e}±0.017
	25	22.00^{b}±0.81	7.10^{c}±0.1	0.92^{a}±0.030
G (85%SFO+ 15% MKO)	0	00.51^{n}±0.05	0.05^{o}±0.005	0.096^{o}±0.003
	5	04.10^{l}±0.15	0.91^{kl}±0.06	0.223^{mn}±0.004
	10	10. 10^{j}±0.36	1.78^{k}±0.02	0.40^{j}±0.02
	15	14.02^{gh}±0.20	2.87^{h}±0.10	0.45^{i}±0.017
	20	18.01^{d}±0.26	5.03^{e}±0.18	0.58^{f}±0.02
	25	22.80^{a}±0.39	7.70^{b}±0.17	0.86^{b}±0.02
I (85%SFO+ 15% MKO+ 400ppm phenolic extract)	0	00.51^{n}±0.05	0.05^{o}±0.005	0.096^{o}±0.003
	5	03.11^{m}±0.18	0.64^{n}±0.04	0.15^{o}±0.01
	10	08.57^{k}±0.51	0.93^{m}±0.06	0.27^{l}±0.01
	15	12.10^{i}±0.52	2.03^{j}±0.04	0.36^{k}±0.02
	20	15.78^{f}±0.38	3.67^{g}±0.09	0.43^{ij}±0.015
	25	20.03^{c}±0.54	5.75^{d}±0.05	0.78^{c}±0.02
LSD 0.05		0.67083961499	0.2219512028	0.02902101296

- Values are the mean of triplicate ± standard division, -Means, within the same column followed by the same letter have no significant difference

4. Conclusion

The present study demonstrated that mango kernel oil (MKO) possesses unique physicochemical properties and a favorable fatty acid profile, characterized by high levels of stearic and oleic acids, which confer remarkable oxidative stability. In addition, MKO and its phenolic extract (MKSE) were found to be rich sources of natural antioxidants, including pyrogallol and gallic acid, which further enhance oil stability. Blending MKO with sunflower oil (SFO) significantly improved the oxidative and frying stability of SFO, while the incorporation of MKSE at 400–600 ppm effectively reduced peroxide, free fatty acids, polar compounds, and polymer formation during repeated frying. These findings highlight the potential of MKO and MKSE as natural alternatives to synthetic antioxidants such as TBHQ. From an industrial perspective, the utilization of MKO and MKSE can add value to mango seeds, which are an underutilized agro-industrial by-product, while providing healthier and more stable oils for food applications. This approach not only improves oil quality and safety but also contributes to waste reduction and sustainability in the food sector.

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