

Monitoring the physicochemical features of sunflower oil and French fries during repeated microwave frying and deep-fat frying

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SUMMARY: This study investigates the effects of repeated microwave frying at different power levels (360W, 600W, 900W) and deep-fat frying on sunflower oil and French fries. The intermittent batch frying cycle was repeated 15 times a day during five consecutive days. The fatty acid profile and physicochemical properties including free fatty acid (FFA), extinction coefficient (K_{270}), total polar compound (TPC), color, viscosity, refractive index of the sunflower oil were determined each day. At the end of the frying period, the highest values of viscosity (76.29cp) and refractive index (1.4738) were detected in microwave frying at 900W power level. TPC level exceeded 25% after the third day of microwave frying at all power levels. The FFA values during microwave frying increased progressively from 0.157% to 0.320-0.379% on the fifth day. The loss of polyunsaturated fatty acids was 37-53% more in the case of microwave frying. The oil quality during microwave frying did not have a significant impact on the oil absorption and total color change of the French fries. Microwave frying, even at higher levels, provided lower oil (8.60-12.32%wb) and moisture contents (35.47-41.24%) compared to deep frying. Microwave frying caused longer processing time and significantly higher levels of degradation of the sunflower oil at all power levels compared to deep frying. However, microwave frying has the advantage of reducing oil absorption. The oil content of French fries was lowered by 20-33% (wb) at the highest power level.

KEYWORDS: Deep-fat frying; Fatty acids profile; French fries; Microwave frying; Physicochemical properties

RESUMEN: Seguimiento de las características fisicoquímicas de aceite de girasol y patatas durante frituras repetidas mediante microondas y freidora. Se estudia los efectos de frituras repetidas mediante microondas a diferentes niveles de potencia (360W, 600W, 900W) y frituras en freidora sobre la estabilidad del aceite de girasol y la calidad de las patatas fritas. El ciclo de fritura intermitente se repitió 15 veces al día durante cinco días consecutivos. Se determinó el perfil de ácidos grasos y las propiedades fisicoquímicas incluyendo ácidos grasos libre (FFA), coeficiente de extinción (K_{270}), compuestos polares totales (TPC), color, viscosidad, e índice de refracción del aceite. Al final del período de fritura, se detectaron los valores más altos de viscosidad (76,29 cp) e índice de refracción (1,4738) en la fritura con microondas a 900 W de potencia. El nivel de TPC excedió el 25% después del tercer día en microondas en todos los niveles de potencia. Los valores de FFA en microondas aumentó progresivamente de 0,157% a 0,320-0,379% al quinto día. La pérdida de ácidos grasos poliinsaturados fue 37-53% en el caso de microondas. La calidad del aceite durante la fritura con microondas no tuvo un impacto significativo sobre la absorción de aceite y el cambio total de color de las patatas. La fritura mediante microondas, incluso a niveles más altos, proporcionó menor contenido de aceite (8.60-12.32% wb) y humedad (35.47-41.24%) en comparación con la freidora. La fritura en microondas produjo niveles significativamente mayores de degradación del aceite a todos los niveles de potencia en comparación con la freidora. Sin embargo, tiene la ventaja de reducir la absorción de aceite; así, el contenido de aceite de las patatas fue un 20-33% (wb) menor al nivel de potencia más alto.

PALABRAS CLAVE: Freidora; Fritura en microondas; Patatas fritas; Perfil de ácidos grasos; Propiedades fisicoquímicas

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1. INTRODUCTION

The popularity of processed potato products, particularly frozen French fries is increasing worldwide. Consumer demand for healthier products has caused a significant increase in research in the area of fried foods. Many of these studies have focused on the reduction of oil uptake (Ziaifar *et al.*, 2008) and oil degradation (Aladedunye, 2015) while keeping the desired characteristics of fried foods during deep fat frying. Deep fat frying is defined as the drying and cooking process of food through contact with oil at a temperature of 120 to 190 °C. During deep frying, the oil is in contact with the air and food at a high temperature and this give rise to the emergence of oxidative, hydrolytic and thermal alterations in the oil. These simultaneous complex reactions cause the formation of many compounds which change the quality of the oil (Velasco *et al.*, 2009). There are many variables affecting the oil degradation. The process of frying is counted as one of the most important factors affecting frying oil quality beside factors like properties and composition of the oil, and the interaction of the food with the frying oil (Aladedunye, 2015; Rossell, 2001). The physicochemical changes occurring in different types of oils during deep frying have been extensively studied by researchers (Siddique *et al.*, 2010; Serjouie *et al.*, 2010; Rehab and El Anany, 2012; Mishra and Sharma, 2014; Zhang *et al.*, 2016). Also, some studies were performed using innovative approaches in the traditional frying methods. Crosa *et al.*, (2014) and Nazarbakhsh *et al.*, (2014) observed that the use of vacuum or some gases during the frying process reduced the rate of oil degradation compared to the traditional frying method.

Microwave frying is proposed as a new technology for improving fried food quality which may be an alternative method to traditional frying (Sahin *et al.*, 2007; Barutcu *et al.*, 2009). Microwave frying was reported to reduce the oil content of potatoes without affecting the other characteristic properties like texture and color (Oztop *et al.*, 2007). Chen *et al.*, (2009) reported similar crust qualities in microwave fried and traditionally fried fish nuggets. It is well known that microwave heating provides shorter heating times compared to conventional heating methods due to the difference in its heating mechanism. Heat generation, creating significant internal pressure, occurs within the food due to mainly its water content during microwave frying and this increases moisture loss from the product and shortens the frying time (Datta, 1990; Feng and Tang, 1998; Sahin and Sumnu, 2009). Gharachorloo *et al.*, (2010) evaluated the physicochemical changes occurring in frying oil and sunflower oil during the microwave frying of potato slices and they stated that microwave frying could be an alternative frying method according to the results of their study. Albi *et al.*, (1997a, b) investigated some physical, chemical parameters and

thermooxidative stability of five edible fats and oils (sunflower oil, high oleic sunflower oil, virgin olive oil, olive oil, and lard) being subjected to microwave heating for 120 min at half-power. They found that microwave heating yielded worse results compared to heating by air convection in an electric oven for 120 min. Bendini *et al.*, (2009) studied the oxidative and hydrolytic degradation of extra virgin olive oil (EVOO), mildly deodorized olive oil (DEO) and blends of these oils that were heated in a microwave oven (750W) for 9 min or heated conventionally for 1hour to reach a similar final temperature. In this study, microwave treatment, contrary to the study conducted by Albi *et al.*, (1997a, b), provided less intense oxidative and hydrolytic degradation in the samples. Borges *et al.*, (2015) showed that the oil type is an important factor affecting the physicochemical properties during microwave heating.

Sunflower oil, which contains a high (around 71%) polyunsaturated fatty acid (PUFA) content (Zambiazzi *et al.*, 2007), is a commonly used vegetable oil consumed in Turkey (Kaya *et al.*, 2008). Depending on the frying conditions, the oil is subjected to many chemical reactions that result in the formation of various compounds and reduction in its PUFA content (Velasco *et al.*, 2009; Zribi *et al.*, 2014; Borges *et al.*, 2015). Several physical (color, viscosity) and chemical parameters (FFA, PV, specific extinction coefficients, TPC, TOTOX value, p-anisidine value, fatty acid composition etc.) are used as indicators of oil quality during deep-fat frying (Serjouie *et al.*, 2010; Osawa and Gonçalves, 2012). The use life of frying oils was defined by different quality parameters by different authors (Sebastian *et al.*, 2014). The quality of fried food depends on the quality of the frying oil since the majority of the compounds, deleterious to health, formed in the oil during frying has been shown to be absorbed by the food (Ziaifar *et al.*, 2008). Sebedio *et al.*, (1990) analyzed both the lipids extracted from the frozen pre-fried French fries after final frying and the frying oil and they observed similar quantities of polar components, polymers and similar 18:1 fatty acid profiles. It is stated also by other researchers that the frying oil may represent the one extracted from the fried food (Pérez-Camino *et al.*, 1991; Dobarganes *et al.*, 2000). Moreover, the oil content of fried products is another important quality criterion that has to be taken into consideration. Oil uptake during frying is known to be effected by many factors including frying temperature and time, moisture content, oil type and quality, interfacial tension, pressure and surface area. However, there is no study in the literature on the evaluation of the effect of oil degradation during repeated microwave frying at different power levels on the quality of finish-fried French fries. Therefore, the main objective of this work is to investigate the effects of repeated microwave frying at three different power levels on

the degradation of sunflower oil and on the oil content, moisture content and total color change of French fries. In addition, the results were compared with the ones obtained during deep-fat frying.

2. MATERIALS AND METHODS

2.1. Materials

Frozen, par-fried French fries were purchased from local supermarket. The sunflower oil used in finish frying was obtained from a local oil company (Çotanak, Ordu, Turkey). A fatty acid methyl ester (FAME) standard mixture (Restek Food Industry FAME Mix, cat# 35077) was purchased from Superchrom (Milan, Italy). All other chemicals were obtained from Merck (Darmstadt, Germany) and Sigma Chemicals Co. (St. Louis, United States) and were of analytical grade.

2.2. Frying Process

Finish frying was carried out in a domestic microwave oven (Bosch HMT84G421) and in a commercial bench-top deep-fat fryer (Tefal, France) with 2.1lt oil capacity. For microwave frying, 2L of sunflower oil was placed in a glass container with a total capacity of 4lt and heated from room temperature to a frying temperature of 180 ± 1 °C by using 360W, 600W or 900W power levels. A fiber optic temperature probe (FISO Technologies, Inc, Quebec, Canada) was used to follow the oil temperature. The initial heating time of the oil from room temperature to 180 ± 1 °C lasted 65, 33 and 25 minutes at the power levels of 360W, 600W or 900W, respectively. At each power level, French fries (50 g) were fried for 3 min. The power level was maintained during this time. After each batch, the oil was allowed to cool for 15 min and then reheated to 180 ± 1 °C. This intermittent batch frying cycle was repeated 15 times a day for five consecutive days. At the end of each day, the oil was covered and left at room temperature overnight. Deep-fat frying was performed using the same frying cycle as the microwave frying. It took 9 min to heat the oil in the fryer from room temperature to 180 ± 1 °C. French fries were fried at 180 ± 1 °C for 3 min in 2L of sunflower oil. The average treatment time that included initial heating, frying, cooling and reheating of oil, took 5.6 hours on the first day of deep-fat frying while the same frying cycle lasted 7.4, 7.5 and 11.6 hours on the first day of microwave frying at power levels of 900W, 600W and 360W, respectively. The potato samples fried at the end of the first, third and fifth days were used for further analysis. 100ml of oil sample from microwave frying at power levels of 360W (MF360), 600W (MF600), 900W (MF900) and from deep-fat frying (DF) at 180 ± 1 °C were collected, put in sealed glass and kept at -18 °C for further analysis at the

end of each day. Since there was no replenishment of oil, the amount of oil remaining reduced to 1.5lt at the end of the frying period. Initially, the ratio between the surface of the glass container and the oil volume was 0.24cm^{-1} and changed to 0.33cm^{-1} after the fifth frying operation. The surface to oil ratio in the fryer changed from the initial value of 0.21cm^{-1} to 0.27cm^{-1} after the fifth frying operation.

2.3. Analysis of Oil

The free fatty acid (FFA) content and the extinction coefficient (K_{270}) were determined according to AOCS official methods of Ca 5a-40 and Ch 5-91, respectively (AOCS, 2005). K_{270} was calculated by using the following formula. The absorbance values for K_{270} were measured at 270nm using a UV-VIS spectrophotometer (UV-mini 1240, SHIMADZU).

$$K\lambda = E\lambda / (c*s) \quad (1)$$

where:

$K\lambda$ = specific extinction at wavelength λ ;
 $E\lambda$ = extinction measured at wavelength λ ;
 c = concentration of the solution in g/100 ml;
 s = path length of the quartz cell in cm;

Fatty acids were evaluated as their methyl esters according to the AOAC method 996.06 (AOAC, 1990). One μL of sample was injected (1:100 split ratio) into a Shimadzu GC-2010 gas chromatograph equipped with a flame ionization detector (FID). A TR-CN100 capillary column (Teknokroma Analitica SA, Barcelona, Spain) of 100 m length and 0.25 mm internal diameter was used. Helium was used as carrier gas at 250 kPa. Initial oven temperature was 140 °C during the first 5 min and the final temperature was kept at 240 °C (4 °C/min) for 20 min. FAME were identified through a comparison of their retention times versus A FAME standard mixture (Restek Food Industry FAME mix37). The results were expressed as the percentages (area %) of individual fatty acids in the lipid fraction.

A Testo 270 instrument (Lenzkirch, Germany) was used to obtain the TPC values of sunflower oil. The sensor was calibrated using the reference oil having a TPC value of $3.5\pm 0.5\%$ according to the manufacturer's instructions. Before TPC measurement, the sensor was immersed in the reference oil heated to approximately 50 °C for reference value adjustment. Refractive indexes of the oil samples were determined by using a hand-held refractometer (Krüss, DR201-95), calibrated against pure water at 25 °C. Oil color parameters of redness (R) and yellowness (Y) were measured by Lovibond Tintometer (PFX 880). A Vibro Viscometer (SV-10 Series, A&D Company, Limited, Japan) was used to obtain the viscosity (cp) of the oil samples at 25 °C.

2.4. Analysis of Fried French Fries

The moisture content of fried French fries was determined in a forced convection oven (NST-120, Ankara, Turkey) at 105 °C up to constant weight (AOAC, 1984). The oil content of the fried French fries was measured after being dried and ground into small particles. Then, Soxhlet extraction was performed for 6 hours using n-hexane as solvent (AOAC, 1984). CIE L^* , a^* , b^* color parameters of the fried French fries were obtained using a Minolta Chromameter CR-400. The total color change (ΔE) was calculated by using the formula given below:

$$\Delta E = \left[(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2 \right]^{1/2} \quad (2)$$

where, L_0 , a_0 and b_0 are reference values belonging to the color of frozen par-fried French fries ($L_0 = 77.8$, $a_0 = 1.3$, $b_0 = 12.9$).

2.5. Statistical Analysis

The frying experiments were carried out in triplicate under the same experimental conditions and the results were expressed as mean \pm standard deviation (SD). The results were analyzed by ANOVA (Analysis of Variance) followed

by Tukey's multiple comparison test ($p < 0.05$) (Minitab, version 17).

3. RESULTS AND DISCUSSION

Figure 1 shows the changes in the free fatty acid (FFA) values of sunflower oil during different frying treatments. During deep-fat frying, the FFA values of sunflower oil were found to rise to 0.261 (% oleic acid) at the end of 3 days and then to remain statistically stable. Mudawi *et al.*, (2014) reported that the FFA of sunflower oil increased significantly as a result of frequent use in the frying of potato chips. There was a gradual rise in the FFA of sunflower oil during microwave frying. This finding is consistent with the literature. Hassanein *et al.*, (2003) showed that the acidity value of different extracted oils (sunflower, soybean and peanut) increased continuously during microwave heating for 18 min. Gharachorloo *et al.*, (2010) reported that the acid value of sunflower oil rose from 0.24 to 0.44 when potato slices were microwave-fried for 20 min at 550W power level for five successive days. Borges *et al.*, (2015) determined a steady and continuous increase in the free acidity of crude baru oil during microwave heating (1000W) for 15 min. However, they did not observe a similar trend for crude soybean oil. Ghosh *et al.* (2014) heated 40gr of refined soybean oil and sesame oil for 5, 10, 15 and 20 min at different power levels (500W, 650W and 800W) in a domestic microwave oven. They recorded oil temperatures as 76 °C and over 300 °C at

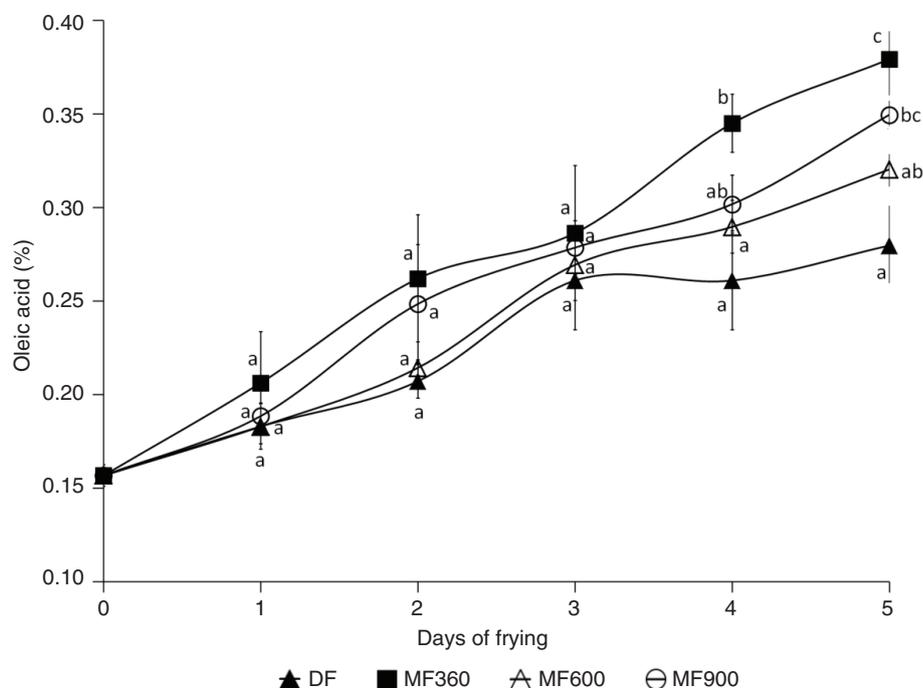


FIGURE 1. Changes in free fatty acid (FFA) values in sunflower oil during microwave frying at 360W (MF360), 600W (MF600), 900W (MF900) and deep-fat frying (DF) of frozen French fries at 180 °C. Error bars indicate the SD of the mean of three replicates (n=3). Means containing different letters in the same day are significantly different ($p < 0.05$).

the lowest and highest powers, respectively. The acidity values for both oils did not change much compared to initial value at the lowest power level while it increased drastically after 10 minutes at the highest power level. In this study, the lowest power level resulted in slightly higher FFA values throughout a 5-day frying period. The FFA values of MF360, MF600, MF900 and DF oil samples were increased from 0.159 to 0.379, 0.320, 0.350 and 0.280 (% oleic acid), respectively, at the end of the frying period. Although microwave frying caused slightly higher FFA values compared to deep-fat frying throughout the frying period, this difference was not significant until day three. During frying, hydrolytic reactions result in the formation of FFAs. The hydrolysis reaction, which is the breakage of the ester bond of triglycerides into glycerol and free fatty acids, is known to be important due to the high moisture content of most foods. A higher rate of moisture removal from French fries during microwave frying (Table 5) may increase the rate of hydrolytic reaction thus leading to the formation of a higher amount of FFA in sunflower oil. In the literature, when we look at the studies comparing the effects of microwave heating and conventional heating on oil degradation, we see that both the time and type of process are important factors affecting the degree of hydrolytic degradation (Albi *et al.*, 1997 a,b; Bendini *et al.*, 2009). Albi *et al.*, (1997a, b) stated that microwave energy may increase the effects of temperature by leading some zonal over-heating in the oil. In this study total processing time

without cooling time was 16.4, 17.4 and 32.7 hours during microwave treatment at 900W, 600W and 360W, respectively, while it was 9.4 hours during deep frying. The temperature of oil was around 155 ± 5 °C after a 15min cooling period. This means that during microwave treatment, the oil was exposed to microwave energy at high temperatures. Longer exposure time to the combination of microwave energy and temperature clearly increased the level of FFA in microwave treated oil, especially at the lowest power level.

The evolution of K_{270} values during frying are displayed in Figure 2. K_{270} value increases with an increasing amount of secondary oxidation compounds (Laguerre *et al.*, 2007). The K_{270} values of sunflower oil increased steadily during deep-fat frying from 1.14 to 3.87. This result is in accordance with previous studies. Chirinos *et al.*, (2011) showed that the conjugated triene values of soybean oil reached nearly 4 during the frying of potato pieces at 180 °C at the end of 6 days. The K_{270} values remained nearly unchanged, ranging from 4.0-4.5 after a rapid increase during microwave frying. Significantly higher values of K_{270} were recorded during microwave frying compared to deep-fat-frying and this difference was more apparent during the initial days of the treatments. This is thought to be due to the difference in the heating mechanisms between the two methods. During microwave heating, two mechanisms, which are dipolar rotation and ionic polarization, are responsible for heat generation (Decareau and Peterson, 1986;

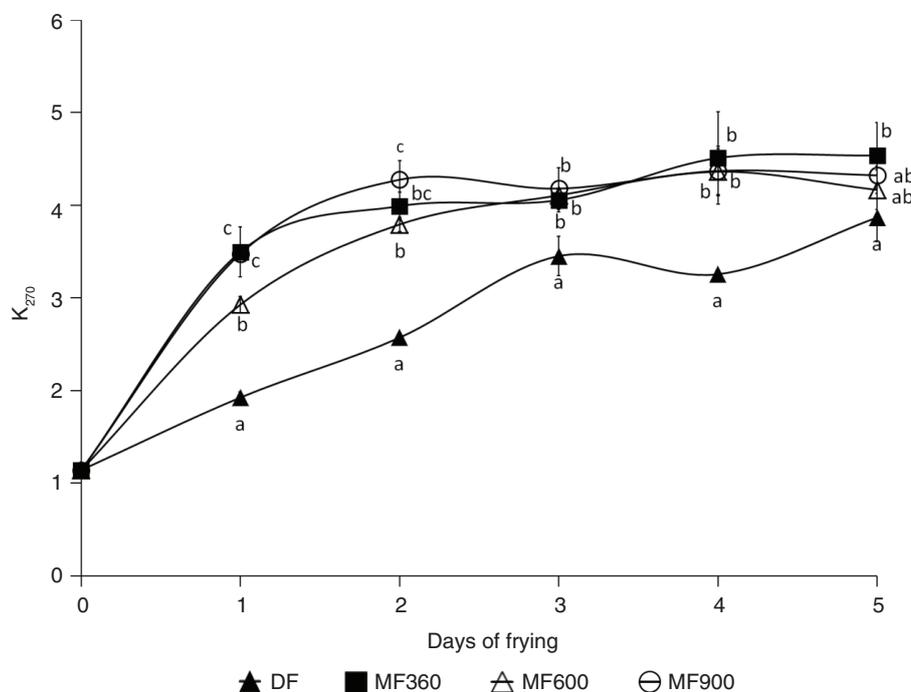


FIGURE 2. Changes in K_{270} values in sunflower oil during microwave frying at 360W (MF360), 600W (MF600), 900W (MF900) and deep-fat frying (DF) of frozen French fries at 180 °C. Error bars indicate the SD of the mean of three replicates ($n=3$). Means containing different letters in the same day are significantly different ($p < 0.05$).

Knutson *et al.*, 1987). The energy lost from the dipole by molecular friction and collisions gives rise to dielectric heating (Gabriel *et al.*, 1998). Albi *et al.*, (1997b) obtained higher K_{270} values in different types of oils during microwave heating compared to conventional heating and they reported that the internal friction of the molecules during microwave heating may be the reason for the formation of higher amounts of trienes, unsaturated ketones or aldehydes. It is known that microwaves interact in different ways with different food components and it has been speculated in the literature that microwave energy exposure, especially at high temperatures, results in the formation of free radicals in high amounts. Yoshida *et al.*, (1991) stated that the decomposition of hydroperoxide formed in highly unsaturated oils occurs rapidly before reacting with tocopherols during microwave heating.

The effects of different treatments on the refractive index and viscosity of oil samples are given in Table 1. The trend for the changes in refractive index values of oil was similar at different power levels of microwave frying. Refractive index values reached a plateau after an initial increase. However, the data from deep-fat frying seems to be erratic. It was found that the power level has a significant effect on refractive index values after the first day. The refractive index values on the last day of the frying period decreased in the order of MF900 > MF600 > DF > MF360. Regardless of the method used, the viscosity of samples showed a linear ($r^2 \geq 0.98$) increase during frying. This is an expected result since the formation of many polymeric compounds as frying proceeds leads to an increase in viscosity (McGill, 1980). Lower viscosity values were recorded during deep-fat frying compared to microwave frying. The viscosity values of DF, MF360, MF600 and MF900 samples increased from 37.67 centipoise (cp) to 48.51, 69.56, 67.76 and 76.29 cp at the end of the frying period, respectively.

A different variety of polar compounds, oxidized and dimerized triglycerides, FFAs, monoglycerides, diglycerides, dimers, trimers tetramers etc. are formed during frying (Velasco *et al.*, 2009). Total polar compound (TPC) (%) values measured by the Testo 270 sensor are given in Figure 3. The measurement of TPC with food oil sensors is a rapid way of monitoring oil quality during deep frying and it is regarded as a reliable method for the determination of TPC by some authors (Croon *et al.*, 1986; Marmesat *et al.*, 2007; Osawa and Gonçalves, 2012). The TPC of sunflower oil increased linearly for all treatments during frying. This is an expected result since a significant increase in total polar compounds, measured by different techniques, in various types of frying oils with increasing frying time was recorded in the literature (Gharachorloo *et al.*, 2010; Chen *et al.*, 2013). Many countries have established a regulatory limit for TPC of around 23%-29% (Gertz, 2000). This level is exceeded after the first day during microwave frying at the 360W power level and after

TABLE 1. Refractive index (25 °C) and viscosity (cp) (25 °C) of sunflower oil during microwave frying at 360W (MF360), 600W (MF600), 900W (MF900) and deep-fat frying (DF) of frozen French fries at 180 °C

Days of frying	Refractive Index (25°C)				Viscosity (cp) (25°C)			
	DF	MF360	MF600	MF900	DF	MF360	MF600	MF900
0	1.4710±0.00A ^{a,b}	1.4710±0.00Aa	1.4710±0.00Aa	1.4710±0.00Aa	37.67±0.03Aa	37.36±0.03Aa	37.67±0.03Aa	37.67±0.03Aa
1	1.4732±0.00Cd	1.4720±0.00Ba	1.4723±0.00Bb	1.4731±0.00Bc	39.74±0.02Bb	45.20±0.06Bd	38.80±0.05Ba	43.61±0.02Bc
2	1.4732±0.00Cc	1.4720±0.00Ba	1.4725±0.00Bb	1.4736±0.00Cd	41.45±0.04Ca	53.76±0.13Cd	47.41±0.09Cb	50.84±0.03Cc
3	1.4707±0.00Aa	1.4721±0.00Bb	1.4729±0.00Cc	1.4739±0.00Cd	44.53±0.03Da	60.29±0.07Dc	55.57±0.12Db	61.42±0.01Dd
4	1.4708±0.00Aa	1.4722±0.00Bb	1.4731±0.00Cc	1.4736±0.00Cd	45.42±0.02Ea	65.23±0.11Ec	61.19±0.09Eb	67.44±0.08Ed
5	1.4725±0.00Bb	1.4722±0.00Ba	1.4731±0.00Cc	1.4738±0.00Cd	48.51±0.03Fa	69.56±0.11Fc	67.76±0.11Fb	76.29±0.06Fd

^aCapital letters shown in the same column compare the frying days for each of the frying conditions.

^bSmall letters shown in the same row compare the frying conditions per frying day ($p < 0.05$).

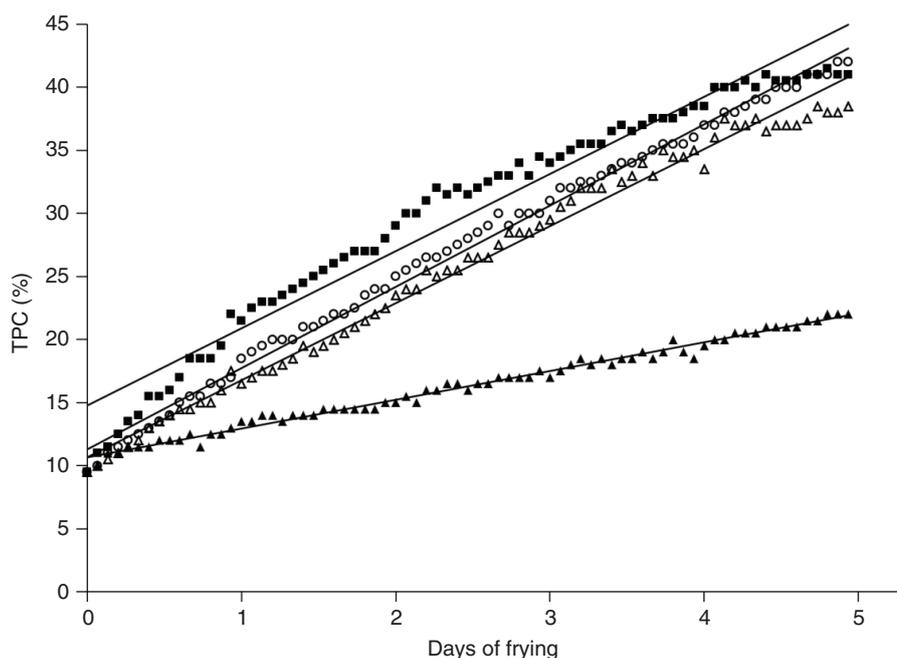


FIGURE 3. Changes in total polar compound (TPC) (%) in sunflower oil during different frying treatments (▲) DF $y=0.15x+10.6$ $R^2=0.988$. (■) MF360 $y=0.41x+14.75$ $R^2=0.956$. (Δ) MF600 $y=0.41x+10.67$ $R^2=0.989$. (○) MF900 $y=0.43x+11.30$ $R^2=0.994$.

the second day during microwave frying at 600W and 900W power levels. Albi *et al.*, (1997a) determined the distribution of polar compounds and demonstrated that thermic degradation was greater than oxidative degradation during microwave heating. Microwave frying was the treatment that produced the greatest TPC values ranging from 38.5-42.0% after five days of treatment, whereas deep-fat frying caused an increase from 9.5% to 22% in this period. This is in close agreement with the other results of this study. The polar compound content was higher in the MF 360 compared to the MF 600 and MF 900 samples especially during the initial days of heating. However, the rate of increase in the TPC value of MF360 sample decreased day by day and the TPC value of MF360 sample reached a similar level as that of the MF900 sample on the last day. The oil was subjected to heat treatment for nearly 11.6 h and 7.4h on the the initial day of microwave frying at 360W and 900W, respectively. During subsequent days of microwave frying, the time required to heat the oil to the desired temperature dropped because of the decrease in the amount of oil and increase in the polarity of the oil, although it was still higher at 360W power level. The total treatment time was 7.6 h and 5.6h on the fifth day at 360W and 900W, respectively. This implies that time of the process cannot be the only factor affecting TPC value.

Color is one of the extensively used physical parameters to evaluate frying oil quality. There was a significant rise in redness (R) and yellowness (Y) values, especially after the initial day of both frying

methods (Table 2). Accumulation of non-volatile decomposition products are shown to change the color of oil (Perkins, 1967). An increase in redness and yellowness in different oil types as a result of frequent use in frying was reported previously (Paul and Mittal, 1996; Mudawi *et al.*, 2014). The interactions between the oil and the French fries may result in an increase in the color values of sunflower oil. Pigments and Maillard reaction products leaching into the frying oil are known to contribute the color changes of frying oil (Velasco *et al.*, 2009). During microwave frying, R values rose from 0.97 to 3.77-4.65 and Y values from 15.0 to 63.5-70.0. Color parameters were significantly affected by power level. 360W microwave power level provided higher color parameters after the first day of frying compared to other power levels. However, the difference between Y values is not statistically significant on the last day.

The fatty acid composition of oil is essential from a nutritional point of view. A high level of polyunsaturated fatty acids (PUFAs) is desirable for human health; on the other hand, PUFAs are known to be unstable under high temperature conditions. The fatty acid compositions of the oil samples are given in Table 3. When we look at the results shown in Table 3, we see that only the major PUFA (C18:2) decreases while the major monounsaturated fatty acid (MUFA) (C18:1) and saturated fatty acids increase after heat treatments. However, these increases are misleading because of the way the FAME data is expressed. Dobarganes and

TABLE 2. Color parameters (R, Y) of sunflower oil during microwave frying at 360W (MF360), 600W (MF600), 900W (MF900) and deep-fat frying (DF) of frozen French fries at 180 °C

Days of frying	R				Y			
	DF	MF360	MF600	MF900	DF	MF360	MF600	MF900
0	0.97±0.06A ^a a ^b	0.97±0.06Aa	0.97±0.06Aa	0.97±0.06Aa	15.00±0.00Ba	15.00±0.00Aa	15.00±0.00Aa	15.00±0.00Aa
1	1.10±0.00Aa	1.40±0.00Bb	1.10±0.00Aa	1.60±0.14Bb	14.00±0.00Ab	16.00±0.00Bc	13.00±0.00Aa	16.00±0.00Ac
2	1.63±0.06Ba	2.45±0.07Cc	2.00±0.00Bb	2.30±0.00Cc	18.27±0.46Ca	39.00±0.00Cd	27.00±0.00Bb	35.00±0.00Bc
3	2.30±0.00Ca	3.25±0.07Dc	2.55±0.07Cab	2.80±0.14Db	24.30±0.00Da	57.00±0.00Dd	39.00±0.00Cb	51.00±0.00Cc
4	3.10±0.00Da	4.45±0.07Eb	2.93±0.26Ca	3.00±0.14Da	39.00±0.00Ea	70.00±0.00Ed	49.90±2.20Db	57.00±0.00Cc
5	5.40±0.00Ed	4.65±0.07Ec	3.77±0.06Da	4.40±0.00Eb	71.35±0.35Fa	70.00±0.00Ea	69.50±0.00Ea	63.50±0.46Ca

^aCapital letters shown in the same column compare the frying days for each of the frying conditions.

^bSmall letters shown in the same row compare the frying conditions per frying day (p < 0.05).

TABLE 3. Quantitation of fatty acids (wt% in oil) of untreated, DF, MF360, MF600 and MF900 sunflower oil samples

Sunflower oil	Days of frying	Total content of FAMES			Percentage of main FAMES						
		Saturated	Unsaturated		Palmitic C16:0	Stearic C18:0	Oleic C18:1	Linoleic C18:2	Others		
			Mono	Poly					Saturated	Unsaturated	
Untreated	0.0	11.7	28.4	59.9	6.1	4.1	28.1	59.8	1.5	0.4	
Deep-fat Frying	1.0	12.5	29.0	58.5	6.7	4.2	28.7	58.4	1.6	0.5	
	2.0	13.1	29.5	57.4	7.3	4.2	29.1	57.2	1.6	0.5	
	3.0	13.9	29.6	56.6	8.1	4.1	29.2	56.4	1.6	0.5	
	4.0	14.8	30.2	55.1	9.0	4.2	29.8	54.8	1.6	0.6	
	5.0	16.2	31.2	52.7	10.1	4.3	30.8	52.4	1.7	0.6	
Microwave Frying	360W	1.0	13.2	30.0	56.8	7.0	4.4	29.6	56.6	1.8	0.6
		2.0	14.4	30.9	54.7	8.0	4.5	30.5	54.5	1.9	0.7
		3.0	15.2	31.2	53.6	8.8	4.5	30.8	53.3	1.8	0.7
		4.0	16.2	32.3	51.5	9.6	4.7	31.8	51.2	2.0	0.8
		5.0	17.1	33.0	49.9	10.3	4.7	32.6	49.6	2.0	0.7
	600W	1.0	12.6	29.1	58.2	6.9	4.1	28.7	58.0	1.6	0.6
		2.0	13.6	30.1	56.3	7.7	4.2	29.7	56.1	1.6	0.6
		3.0	15.2	31.5	53.3	8.7	4.6	31.1	53.1	1.9	0.7
		4.0	16.1	32.2	51.7	9.6	4.6	31.8	51.4	1.9	0.7
		5.0	17.1	32.9	50.0	10.5	4.7	32.5	49.7	2.0	0.7
900W	1.0	13.1	29.8	57.1	7.0	4.4	29.4	56.9	1.8	0.6	
	2.0	13.9	30.4	55.7	7.8	4.4	30.0	55.5	1.8	0.7	
	3.0	15.2	31.5	53.3	8.8	4.6	31.1	53.0	1.9	0.7	
	4.0	16.4	32.4	51.2	9.8	4.7	31.9	50.9	2.0	0.7	
	5.0	17.8	33.4	48.8	10.9	4.8	32.9	48.5	2.1	0.8	

Pérez-Camino, (1988) stated that because of their high polarity, the altered FAME fractions are normally adsorbed into the GC column, and the unaltered ones are the only fractions that are eluted in GC analysis. The data corresponding to treated oil samples given in Table 3 were recalculated proportionally in the case of unsaturated FAME by maintaining the initial content of unsaturated fatty acids

constant (C16:0 and C18:0) (Berdeux *et al.*, 2012) and the estimated values are presented in Table 4. The reduction in the amount of linoleic acid during deep-fat frying (Zhang *et al.*, 2016) and microwave frying (Gharachorloo *et al.*, 2010) was reported previously. In this study, the percentage decrease in linoleic acid contents were 36.3%, 43.2%, 43.3% and 46.7% for DF, MF360, MF600 and MF900 samples.

TABLE 4. Estimated quantitation of FAME (wt% in oil) of untreated, DF, MF360, MF600 and MF900 sunflower oil samples

Sunflower oil	Days of frying	Total content of FAMES			Percentage of main FAMES						Estimated nonpolar FAME	
		Saturated	Unsaturated		Palmitic C16:0	Stearic C18:0	Oleic C18:1	Linoleic C18:2	Others			
			Mono	Poly					Saturated	Unsaturated		
Untreated	0.0	11.7	28.4	59.9	6.1	4.1	28.1	59.8	1.5	0.4	100.0	
Deep-fat Frying	1.0	11.7	27.2	54.9	6.1	4.1	26.9	54.7	1.5	0.5	93.8	
	2.0	11.7	26.3	51.2	6.1	4.1	26.0	51.0	1.5	0.5	89.2	
	3.0	11.7	24.9	47.7	6.1	4.1	24.6	47.5	1.5	0.5	84.3	
	4.0	11.7	23.9	43.6	6.1	4.1	23.6	43.4	1.5	0.5	79.2	
	5.0	11.7	22.6	38.1	6.1	4.1	22.3	38.1	1.5	0.5	72.6	
Microwave Frying	360W	1.0	11.7	26.6	50.4	6.1	4.1	26.3	50.2	1.5	0.5	88.7
		2.0	11.7	25.0	44.3	6.1	4.1	24.7	44.1	1.5	0.5	81.1
		3.0	11.7	24.0	41.2	6.1	4.1	23.6	40.9	1.5	0.6	76.9
		4.0	11.7	23.3	37.2	6.1	4.1	23.0	37.0	1.5	0.6	72.2
		5.0	11.7	22.6	34.1	6.1	4.1	22.3	34.0	1.5	0.5	68.5
	600W	1.0	11.7	27.0	54.0	6.1	4.1	26.6	53.8	1.5	0.6	92.6
		2.0	11.7	25.9	48.4	6.1	4.1	25.5	48.2	1.5	0.5	86.0
		3.0	11.7	24.3	41.1	6.1	4.1	23.9	40.9	1.5	0.5	77.1
		4.0	11.7	23.3	37.5	6.1	4.1	23.0	37.3	1.5	0.5	72.5
		5.0	11.7	22.5	34.1	6.1	4.1	22.2	33.9	1.5	0.5	68.3
900W	1.0	11.7	26.6	51.0	6.1	4.1	26.3	50.8	1.5	0.5	89.3	
	2.0	11.7	25.6	46.9	6.1	4.1	25.2	46.7	1.5	0.6	84.1	
	3.0	11.7	24.2	40.9	6.1	4.1	23.9	40.7	1.5	0.5	76.9	
	4.0	11.7	23.0	36.4	6.1	4.1	22.7	36.2	1.5	0.5	71.2	
	5.0	11.7	21.9	32.0	6.1	4.1	21.6	31.8	1.5	0.5	65.6	

There was a linear decrease in both monounsaturated fatty acid (MUFA) and PUFA contents of all samples with increasing days of frying. The decline in PUFA content was found to be higher for microwave heated ones. Dobarganes and Pérez-Camino, (1988) stated that polar FAME is a measurement of the altered fatty acids and is considered a good measurement of thermo-oxidative degradation. In their research, they showed that the measured values of polar FAMES by GC analysis were very close to that obtained by estimation. The estimated polar compounds, shown in Table 4, were between 5.4 and 34.4% for all applied conditions. These values are in accordance with the literature values given for used frying oils (Dobarganes and Márquez-Ruiz, 1998). The oxidation of polyunsaturated fatty acids results in the formation of conjugated structures. An increase in the K_{270} value is reported to be related to the formation of conjugated trienes (Bendini *et al.*, 2009). The rate of increase in K_{270} values was significantly higher during the initial days of microwave frying compared to deep frying which may indicate that microwave frying increased the degree of oil oxidation.

During microwave frying, the sunflower oil sample had higher values of FFA, K_{270} , TPC, and viscosity and lower content of PUFA compared to the conventional frying method. The oil samples were exposed to higher temperatures for longer periods and also to microwave energy during microwave frying. It is recorded in the literature that when the temperature was kept below 40 °C, microwave energy alone had no effect on oil degradation (Albi *et al.*, 1997a, b). Both the time and the type of process are thought to be important factors in the degree of oil degradation. However, it is not possible to specify which factor is effective at what level. The microwave power level was found to be a significant factor in the investigated parameters. While the TPC, viscosity and reduction in PUFAs contents of the 360W oil samples were higher during the initial days of microwave frying they were higher in the 900W samples on the last day of frying. The increase in TPC and consequently the decrease in PUFA content was an expected result.

Frozen par-fried French fries have initial moisture and oil contents of 71.7% (wb) and 4.1% (wb), respectively. The oil content, moisture content and

TABLE 5. Moisture content, oil content and ΔE values of French fries during microwave frying at 360W (MF360), 600W (MF600), 900W (MF900) and deep-fat frying (DF)

	Days of frying	DF	MF360	MF600	MF900
Moisture content (%wb)	1	52.95±0.98B ^a c ^b	41.41±0.85Ab	37.20±0.51Aa	35.47±0.64Aa
	3	51.22±0.65ABd	47.68±0.45Bc	41.24±0.43Bb	37.73±0.30Aa
	5	49.15±1.02Ab	48.70±1.22Bb	40.61±0.02Ba	39.58±1.07Aa
Oil content (%wb)	1	13.04±1.40Ac	12.32±0.59Ab	9.39±0.29Aa	10.50±0.53Aa
	3	11.81±0.23Ac	10.25±0.09Ab	8.60±0.74Aa	8.60±1.02Aa
	5	12.79±0.78Ac	9.76±1.03Ab	8.78±1.17Aab	8.61±0.91Aa
Total color change (ΔE)	1	25.96±1.44Aa	29.25±1.90Aab	30.28±1.27Aab	31.76±1.65Ab
	3	30.55±1.77Ba	30.68±1.98Aa	29.78±1.74Aa	31.09±1.32Aa
	5	31.69±1.15Ba	28.29±1.64Aa	30.75±1.82Aa	32.65±1.65Aa

^aCapital letters shown in the same column compare the frying days for each of the frying conditions.

^bSmall letters shown in the same row compare the frying conditions per frying day ($p < 0.05$).

ΔE values of fried French fries are represented in Table 5. The oil contents of the samples were between 11.81-13.04% (wb) during deep-fat frying while they varied in the range of 8.60-12.32% (wb) during microwave frying. It was reported in literature that the oil content of finished French fries varies from 10–15% (wb) (Miranda and Aguilera, 2006). Microwave fried French fries had lower oil content and moisture content when compared to the ones fried conventionally. This result is in accordance with the literature. In their study, Oztop *et al.*, (2007) interpreted that the diffusion of oil into the product is limited by a high evaporation rate of water during microwave frying. It is reported that oil is absorbed by potato mainly during cooling not during deep-fat frying (Moreira *et al.*, 1997). However, the mechanism of oil absorption is still not clear during microwave frying. There was a slight decrease in the oil content of all samples with increasing levels of oil degradation, however, this difference was not found to be statistically significant. Similar findings were recorded in the literature during the deep-fat frying of different types of foods. Dobarganes *et al.*, (2000) recorded no significant difference in the oil contents of frozen, pre-fried foods due to the quality of the oil used. A similar finding was reported for tortilla chips fried in refined soybean oil (Tseng *et al.*, 1996). In general, the lowest power level caused greater oil absorption during microwave frying. As expected, microwave frying increased the rate of moisture removal compared to deep-fat frying. The microwave power level was found to be effective on the moisture content of samples. Moisture content decreased as the power level increased. There was a slight rise in the moisture content of microwave fried samples with increasing oil degradation.

Color is another quality criterion of deep fat fried products. The total color change (ΔE) of microwave

fried samples increased with an increasing microwave power level on the initial and final days of frying, although this difference was not found to be statistically significant. The ΔE value of deep-fat fried samples increased gradually with increasing frying days while that of the microwave fried ones stayed nearly constant. The color changes of foods during frying are reported to be influenced by some factors like the chemical browning reactions in food, oil absorbed by food, time and temperature of frying process, etc. (Loewe, 1993). Microwave frying at the highest power level provided significantly higher ΔE value of French fries compared to deep-fat frying on the initial day. For the subsequent days, the ΔE value of French fries was found to be similar for all frying treatments.

4. CONCLUSIONS

Microwave frying increased the rate of sunflower oil degradation compared to deep-fat frying. The TPC level reached 39-42% at the end of microwave frying trials while it was still under 25% at the end of the deep-fat frying period. Likewise, the loss in the amount of polyunsaturated fatty acids was higher in the case of microwave frying. However, microwave frying provided an advantage in French fry quality by lowering the oil content. Oil degradation did not have a significant effect on the oil uptake during both frying methods. Microwaves are reported to offer many advantages in certain food processing operations with regards to time, space and energy savings, as it ensures the preservation of nutritional value, process control, and selective heating. However, the longer period of time required to heat the oil to frying temperature was one of the major disadvantages of using microwave energy during a repetitive frying process. Cleaning the oil that splashes out into

the microwave also requires extra time after each frying process. More importantly, microwave frying resulted in significantly higher levels of degradation of sunflower oil at all power levels. The differences in the heating mechanisms together with the duration of the process are thought to be important factors in this respect. Especially during the initial days of frying, these disadvantages may be minimized to some extent by using higher power levels. In addition, the oil absorption of French fries decreased by increasing the microwave power level. However, on the last day of treatment, the higher power level caused higher values of TPC, viscosity and a higher reduction in PUFA contents in the oil. This study showed that both the degradation rate of sunflower oil and the quality of French fries were influenced by the level of power during microwave frying and the highest power level provided better results during the initial days of a repetitive frying process.

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