Suitability of contact angle measurement as an index of overall oil degradation and oil uptake during frying

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ABSTRACT

The aim of the work was to investigate the suitability of contact angle measurement as an index of overall oil degradation phenomena and oil uptake of French fries during frying. In order to measure the contact angle, an image analysis method was developed and applied to four vegetable oils (palm oil, palm super olein, sunflower oil and a blend of hazelnut and high-oleic sunflower oil) in actual frying experiments. With liquid oils, contact angle modification proved to be a sound index of overall oil degradation, being inversely correlated with oil acidity, peroxide value, total carbonyl compounds, K_{232}, and viscosity. A significant correlation between contact angle and potato oil uptake was found for sunflower oil. For the other oils, factors such as the structure of food subjected to frying or the oil melting point and viscosity seem to be important in influencing oil uptake.

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1. Introduction

Deep-fat frying is a cooking process appreciated by consumers for the desirable taste and texture imparted to food. The process involves both mass transfer, mainly represented by water loss and oil uptake, and heat transfer (Vitrac, Dufour, Trystram, & Raoult-Wack, 2002). Moreover, due to temperature (150–200 °C) and the presence of oxygen and steam released from food, the oil undergoes a series of chemical reactions that decomposes it to form a variety of volatile compounds, as well as monomeric and polymeric products (White, 1991). Thus, the composition of a fresh unused oil is very different from that of an abused frying oil.

In the frying process, cooking is accomplished by direct heat transfer from hot oil to the cold food. As a consequence, the phenomena taking place at the oil–food interface deeply affect the quality of the fried food. In particular, many oil degradation products formed during frying are polar compounds that are able to reduce the surface tension at the oil–food interface (Blumenthal, 1991). When the oil is unused, the interfacial tension is very high because oil is a non-aqueous material and food is mainly aqueous. Basically, the two phases are immiscible. This means that the surrounding hot oil has little possibility of clinging to the food surface, contrasting with the tension of steam escaping from food (Blumenthal, 1991). The efficiency of heat transfer is thus hampered and food remains uncooked without achieving the desired flavour and crispy characteristics. As the oil continues to be used, the interfacial tension is decreased and the quality of the food is improved. Blumenthal (1991) described five different stages through which the oil progresses, each producing different qualities of the fried food.

The interactions between oil and food also involve mass transfers. Due to the surrounding heating media, in fact, water evaporates from the food surface, creating a diffusion gradient, driving inner water toward the surface, and thus producing a continuous steam flow. Water evaporation leaves voids for the fat to enter later; that is why fat uptake is largely proportional to moisture loss (Gamble, Rice, & Selman, 1987). Moreover, the initial moisture content of food dramatically affects the final oil uptake (Moreira & Barrufet, 1998).

According to Bouchon, Aguilera, and Pyle (2003), the overall oil uptake in the fried food is composed of three oil fractions: structural oil (absorbed during frying), penetrated surface oil (suctioned during cooling), and surface oil, although the first is often negligible because, as long as steam escapes from the food, a positive pressure prevents oil absorption into food. Several studies have demonstrated that the largest part of the frying fat is taken up on cooling after removing food from the frying fat (Moreira & Barrufet, 1998; Moreira, Sun, & Chen, 1997; Ufheil & Escher, 1996). Basically, two mechanisms govern this fat uptake: the condensation effect and

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the capillary effect. The former is a consequence of water vapour condensation in the pores of the crust of food, resulting in sucking up, into the crust, of the oil attached to the food surface; the latter is determined by the wetting characteristics of the oil (Mellema, 2003).

The wettability of a liquid on a solid surface is expressed by the contact angle between the liquid and the solid (Gomes da Silva & Singh, 1995). The concept is illustrated by a small drop of liquid resting on a flat horizontal solid surface. When the contact angle approaches the zero value, the liquid spreads over the solid, wetting it; alternatively, for a value higher than 90° the liquid does not wet the solid and does not enter capillary pores. Thus, in deep-fat frying, the contact angle determines (together with the sucking-up phenomenon) which pores will be filled by the oil. Interfacial tension is also very important because it governs whether the external oil would overcome the energy barrier due to the pressure gradient (Miller & Neogi, 1985), built up by water evaporation. For a system at equilibrium, the two physical properties are related by Young's equation:

$$\gamma_{la}\cos(\theta) = \gamma_{sa} - \gamma_{sl}$$

where: θ, contact angle; γ, surface tension (N/m); s, solid; l, liquid; a, air. Fig. 1 represents contact angle at equilibrium on a solid surface according to Young's equation.

In frying experiments using soybean oil or different frying media made of surfactants and a restructured potato product as a food model, Pinthus and Saguy (1994) found a power relationship between the initial interfacial tension and oil uptake, and a linear relationship between oil uptake and contact angle.

During frying, oil degradation also has a role in fat uptake, because oil absorption is facilitated by the reduction of the interfacial tension between food and oil, and by the increasing amount of the oil at the food surface due to the formation of polymeric compounds affecting oil viscosity (Dobarganes, Márquez-Ruiz, & Velasco, 2000). A high oil viscosity and/or the use of hard fats will lead to less easy drainage of oil when the fried food is removed from the fryer and food temperature drops quickly. On the other hand, an increased oil viscosity should impair the oil transfer from the surface to inner food, especially in the small pores. The phenomena are thus contrasting in part, and a minor positive correlation between oil uptake and the oxidative degradation of frying medium has been reported (Mellema, 2003).

Classical methods to measure contact angle have been reviewed by Neumann and Good (1979). The most widely used method is the static sessile drop method, involving a goniometer as measuring device and employing an optical system to view the outline of the drop on the surface. Older systems have used a microscope optical system, while current generation systems adopt precision optics and charge-couple device camera with image processing hardware and software to enhance the performance of contact angle analysis, making it easier, and more precise.

The aim of the work was to investigate the suitability of contact angle measurement as an index of overall oil degradation phenomena and oil uptake of Fren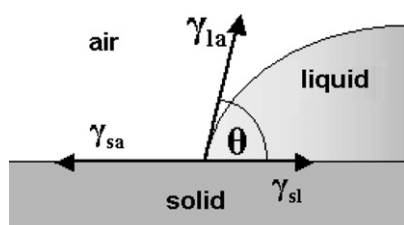ch fries in actual frying experiments. To verify this suitability, correlations between contact angle and common degradation indices of frying oils were studied. Besides, the correlations between oil degradation indices and the behaviour of potatoes during frying were studied.

2. Materials and methods

2.1. Materials

Four different refined vegetable oils were investigated in this study: palm oil (PO) and palm super olein (double fractionated; PSO) directly provided by a local refinery (Industria Grassi e Oli Raffinati, Orzinuovi, Italy), sunflower oil (SO) and organic frying oil (SHO) made of a blend of high-oleic sunflower oil and hazelnut oil, purchased from a local supermarket. "Vittoria" (from Belgium) and "Bintje" (from Holland) potato varieties were used for frying experiments.

2.2. Frying experiments

Potato strips (9 mm × 9 mm × 60 mm) were prepared and fried as reported in a previous paper (Rossi, Alamprese, & Ratti, 2007). In particular, frying conditions were: set frying temperature, 190 °C; actual frying temperature, 175 °C; potatoes to oil ratio, 25 g:11; potato cooking time, 8 min; break time between two successive frying sessions, 7 min. Frying lasted continuously for 6 h/day with no oil replenishment, for a total of 12 h and 48 frying sessions for PO and SO (frying "Vittoria" potatoes), and 18 h and 72 frying sessions for PSO and SHO (frying "Bintje" potatoes). Because frying experiments were carried out in different seasons, two different potato varieties were used depending on the market availability. In the second group of frying experiments (PSO and SHO), the total frying time was increased from 12 to 18 h, to better highlight the modification phenomena.

2.3. Sampling

Oil (two 50 ml aliquots) and potato samples were taken every 3 h during frying. The two aliquots of sampled oil were immediately cooled and stored in the dark at −20 °C prior to analyses, except for apparent viscosity measurement (4 °C). French fries were drained off for 5 min on a stainless steel sieve and weighed on analytical balance before storage at −20 °C prior to analyses.

2.4. Oil analyses

The following analyses were carried out in duplicate (unless not differently indicated) on both fresh and fried oils.

Acidity was evaluated by titration with 0.1 N NaOH according to the NGD C10-76 method (NGD, 1976a). Results are expressed as g of oleic acid/100 g.

Peroxide value was determined by titration with 0.01 N $Na_2S_2O_3$ according to the NGD C35-76 method (NGD, 1976b). Results are expressed as meq O_2/kg oil.

Total carbonyl compounds were measured according to the method of Endo, Chang, Tagiro-Ndo, and Fujimoto (2001), but without the use of triphenylphosphine, as suggested by the authors (personal communication). The results are expressed as mmol/kg oil, calculated by comparison with a calibration curve prepared with 2,4-decadienal (Sigma–Aldrich GmbH, Steinheim, Germany) in a concentration range of 85–840 µM.

The spectrophotometric index K_{232} was measured according to the NGD C40-02 method (NGD, 2002).

Fatty acid composition was determined by capillary gas chromatography on fatty acid methyl esters obtained according

Fig. 1. Contact angle (θ) of a liquid on a solid surface at equilibrium. γ, surface tension; s, solid; l, liquid; a, air.

to Liebich, Wirth, and Jakober (1991). Gas chromatographic analysis was carried out as reported by Rossi et al. (2007).

The apparent viscosity measurement was carried out using a VOR rheometer (Bohlin Reology AB, Lund, Sweden) equipped with coaxial cylinders, C25, and a 3.95 g cm torsion bar. Analysis was performed at 40 °C and 116 s^{-1} shear rate. Before analysis, oils were first pre-conditioned at 80 °C for 45 min in a water bath to melt any crystal forms, and then cooled to the actual measurement temperature. Results are expressed as mPa s.

Contact angle measurement was performed by image analysis, as first suggested by Michalski, Desobry, Pons, and Hardy (1998), modified as described below. With the aid of a square-cut tip syringe, a 20 μl oil droplet was laid on a glass surface previously cleaned with ethanol and carefully horizontally aligned with the head of a digital video microscope (FSC Microflex Classic, Schölly Fiberoptic GmbH, Denzlingen, Germany). For each oil sample, images of 10 different droplets were taken (20× magnification) at 640 × 480 pixel resolution, working at room temperature. PO and PSO were pre-conditioned at 80 °C for 45 min and then kept at 40 °C until analysis; instead SO and SHO were kept and analysed at room temperature. Digital images were processed with *Image Pro-Plus* 5.0 (Media Cybernetics Inc., Bethesda, MD, USA) software, applying a specific macro purposely developed according to the following steps: (a) grey scale conversion; (b) median and Roberts filters application (to emphasize drop contour); (c) direct measurement of the contact angle on left and right drop portions calculated through an algorithm developed to minimize the coefficient of variation (Fig. 2).

2.5. Potato analyses

Moisture content of raw and fried potatoes (5 g) was assessed gravimetrically at 105 °C (until constant weight). Results are expressed in g/100 g as the average of duplicate analyses.

Fat content of fried potatoes was evaluated by petroleum ether extraction (5 h) in a Soxhlet apparatus on 5 g of minced sample mixed with anhydrous sodium sulphate. Fat content was determined gravimetrically after solvent evaporation. Results are expressed in g/100 g as the average of duplicate analyses.

Potato moisture loss during frying was calculated according to the following equation:

Moisture loss (g/100 g raw potatoes)

$$= \frac{(A \times M) - (B \times M')}{A} \times 100$$

where: A, raw potato weight (g); B, fried potato weight (g); M, raw potato moisture (g/100 g); M′, fried potato moisture (g/100 g).

Potato oil uptake during frying was calculated according to the following equation:

$$\text{Oil uptake (g/100 g raw potatoes)} = \frac{B \times F}{A} \times 100$$

where: A, raw potato weight (g); B, fried potato weight (g); F, fried potato fat content (g/100 g).

2.6. Statistical analysis

Pearson correlation matrix was performed, using Systat 5.03 software for Windows (Systat Inc., USA).

3. Results and discussion

Table 1 shows the contents of saturated (SFA), monounsaturated (MUFA), and polyunsaturated (PUFA) fatty acids of the oils used for the frying experiments. PO and PSO had the highest SFA content, mainly represented by palmitic and stearic acids; SO was very rich in PUFA, mainly as linoleic acid, which makes it particularly sensitive to oxidation, while the SHO blend abounded in MUFA that are more stable toward oxidation reactions (Fatemi & Hammond, 1980).

The most abundant PUFA, linoleic acid, was degraded during frying in the four oils because of lipid oxidation (Fig. 3). By comparison of the slope values shown in the graph, the highest degradation rate was found for SHO, probably due to its lower content of natural antioxidants in comparison to SO (393 mg/kg vs. 475 mg/kg total tocopherols, respectively) and to the lack of tocotrienols in SHO, which are instead present in PO and PSO and act as more effective antioxidant compounds (Rossi et al., 2007).

Table 2 and Figs. 4 and 5 show the modifications of the chemical and physical oil characteristics with the frying time; with the exception of contact angle, all the variables showed increasing trends. The acidity of oils (Table 2) increased due to the hydrolytic degradation of triacylglycerols caused by water vapour escaping from food. Particularly, SO acidity increased at a slightly faster rate, achieving, after 12 h, the highest value (0.76 g/100 g) among the different oils, probably in relation to a greater potato moisture loss, as shown in Table 3. The acidities measured in the different oils after 12 and 18 frying hours, although remaining within acceptable values, were on average higher than the values reported in the literature for palm olein and high-oleic sunflower oil used with a potato to oil ratio similar to ours (Fauziah, Razali, & Nor Aini, 2000), or for a blend of rape-seed oil and palm olein (Negishi, Nishida, Endo, & Fujimoto, 2003). It must be noted that, differently from the cited papers, in the present work no replenishment with fresh oil was done to avoid the dilution of oil degradation products, while keeping constant the potato to oil ratio.

With fresh oils, the peroxide value (PV) and the content of carbonyl compounds, which are indices of primary and secondary lipid oxidation respectively, were higher in SO. Besides a higher PUFA content, also the packaging material and the distribution/retailing conditions of SO may have accounted for these higher oxidation values. The SO sample, purchased from a supermarket, was in fact marketed in a transparent PET bottle, differently from SHO, which was in a dark glass bottle, while PO and PSO were furnished
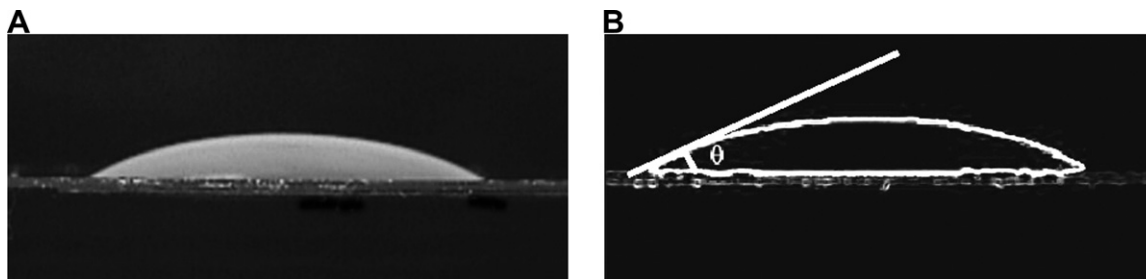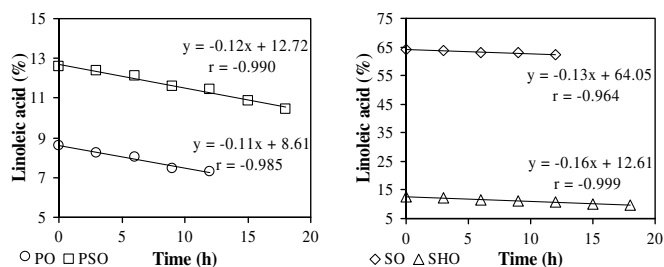

Fig. 2. Oil droplet digital images before (A) and after (B) processing. θ represents the measured contact angle.

Table 1
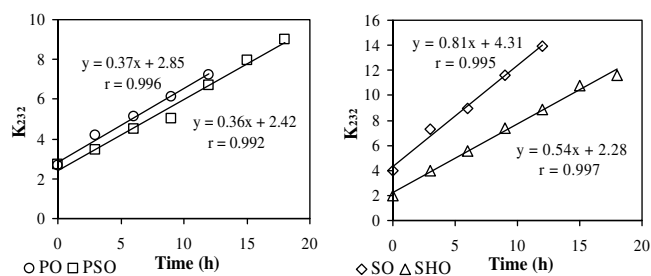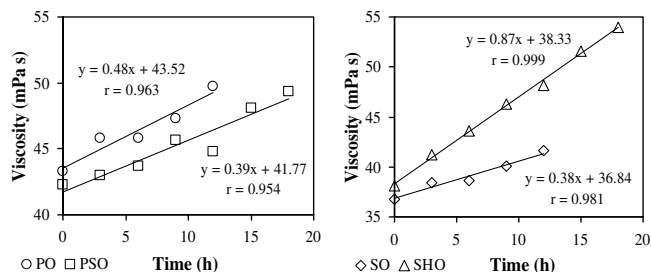Fatty acid composition (%) of the unused frying oils

Oil sample	SFA	MUFA	PUFA
PO	53.2	37.8	9.0
PSO	39.1	47.6	13.3
SO	10.2	24.6	65.2
SHO	7.8	79.1	13.1

SFA, saturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids.

Fig. 3. Linoleic acid degradation during frying. Data points represent mean values. Standard deviations ranged between 0% and 0.32%.

Table 2
Degradation indices and contact angle of oils during frying (mean values ± standard deviations)

Oil sample	Acidity (g/100 g)	Peroxide value (meqO$_2$/kg)	Total carbonyl compounds (mmol/kg)	Contact angle (°)
PO				
0 h	0.09 ± 0.01	0.58 ± 0.10	4.80 ± 0.79	23.6 ± 1.7
3 h	0.17 ± 0.01	2.27 ± 0.06	10.9 ± 0.08	23.5 ± 0.9
6 h	0.29 ± 0.01	3.49 ± 0.01	15.0 ± 0.49	22.5 ± 0.5
9 h	0.44 ± 0.02	5.02 ± 0.03	19.9 ± 0.44	22.5 ± 0.7
12 h	0.61 ± 0.01	6.08 ± 0.17	21.7 ± 0.16	22.8 ± 1.4
PSO				
0 h	0.12 ± 0.01	0.55 ± 0.07	4.38 ± 0.87	22.3 ± 0.7
3 h	0.19 ± 0.01	2.05 ± 0.07	7.04 ± 1.00	23.3 ± 2.7
6 h	0.27 ± 0.01	2.99 ± 0.01	12.2 ± 0.43	21.6 ± 2.8
9 h	0.33 ± 0.01	2.68 ± 0.07	17.4 ± 0.26	22.1 ± 1.9
12 h	0.46 ± 0.01	3.05 ± 0.28	22.1 ± 0.36	22.9 ± 2.6
15 h	0.55 ± 0.02	3.67 ± 0.08	23.6 ± 0.54	22.3 ± 2.4
18 h	0.68 ± 0.01	3.61 ± 0.01	35.0 ± 1.90	22.6 ± 2.3
SO				
0 h	0.11 ± 0.01	2.66 ± 0.06	6.55 ± 0.59	23.1 ± 1.1
3 h	0.23 ± 0.01	3.26 ± 0.10	11.7 ± 0.18	20.4 ± 0.9
6 h	0.40 ± 0.01	4.17 ± 0.08	13.7 ± 0.45	19.3 ± 1.1
9 h	0.57 ± 0.02	5.16 ± 0.10	18.2 ± 1.48	18.5 ± 1.4
12 h	0.76 ± 0.01	6.29 ± 0.01	20.7 ± 1.66	18.2 ± 0.7
SHO				
0 h	0.11 ± 0.01	0.48 ± 0.01	1.89 ± 0.22	19.6 ± 1.3
3 h	0.17 ± 0.01	5.55 ± 0.30	9.62 ± 1.94	18.0 ± 0.7
6 h	0.26 ± 0.02	4.88 ± 0.13	15.5 ± 0.79	17.7 ± 0.8
9 h	0.33 ± 0.01	4.87 ± 0.23	34.3 ± 0.48	17.3 ± 0.5
12 h	0.40 ± 0.02	5.51 ± 0.06	39.7 ± 0.26	16.8 ± 0.7
15 h	0.51 ± 0.02	7.30 ± 0.13	48.1 ± 0.61	16.9 ± 0.7
18 h	0.61 ± 0.02	7.15 ± 0.29	48.4 ± 0.25	16.5 ± 0.7

Fig. 4. Oil K$_{232}$ during frying. Data points represent mean values. Standard deviations ranged between 0.005 and 0.430.

Fig. 5. Apparent oil viscosity (measured at 40 °C) during frying. Data points represent mean values. Standard deviations ranged between 0 and 0.9 mPa s.

by the lowest PV attained by PSO after 18 frying hours. Actually, PSO had the highest total tocopherol content (1064 mg/kg), and was particularly rich in γ-tocotrienol, the tocopherol with the highest antioxidant capacity (Rossi et al., 2007). The superiority of γ-tocopherol/tocotrienol in improving frying oil stability has been also stressed by Kochhar (2001).

K$_{232}$ (Fig. 4), another oxidation index, related to conjugated diene formation, was higher and increased more rapidly in SO, despite the higher degradation rate of linoleic acid observed in SHO.

Oil apparent viscosity at 40 °C (Fig. 5) increased with increased frying time due to the formation of polymeric compounds (Lawson, 1995; Orthoefer & List, 2007), with the highest rate in SHO in accordance with the highest PV and carbonyl compounds formation rates reported above for this oil.

The modification of oil contact angle during frying, as an index of food wettability by the oils, was also studied (Table 2). As using time progresses, several oxidative and hydrolytic degradation compounds are formed, causing a reduction in the food–oil interfacial tension and a concurrent contact angle reduction, according to the Young's equation. In agreement with the oxidation results observed during frying, contact angle was significantly reduced in both SO and SHO, with faster rate in SO. This faster rate is consistent with the faster acidity increase observed in SO, due to the hydrolytic phenomena, yielding surfactant compounds such as mono and diacylglycerols (Blumenthal & Stier, 1991). PO and PSO contact angles, instead, seem fairly stable during the frying time, notwithstanding the degradation of the oils highlighted by the chemical and physical indices. The lack of correlations between PO and PSO contact angles and the indices of oil degradation highlights the insufficiency of the measuring procedure when applied to semi-fluid oils and hard fats. According to the measuring procedure, in fact, the deposition of a 20 μl oil droplet was performed at room temperature on a glass surface. Although PO and PSO were kept fluid at 40 °C until the moment of deposition and droplet image was immediately captured, an early triacylglycerol crystallization, possibly altering the droplet outline, could not be excluded. Such a hypothesis is more acceptable in the case of PO, this oil

by the refinery in lined metal cans. Thus, because of the light catalytic effect, SO could have already been oxidized during the shelf life. Instead, at the end of the frying time, the highest peroxide and carbonyl compound values were measured in SHO, probably in accordance with its lower content of natural antioxidants, as already discussed for linoleic acid degradation rate. The importance of natural antioxidants in reducing the oxidation rate is underlined

Table 3
Moisture loss, oil uptake, and total fat (mean values ± standard deviation) of potatoes during frying

Oil sample	Moisture loss[a] (g/100 g raw potatoes)	Oil uptake (g/100 g raw potatoes)	Total fat (g/100 g fried potatoes)
PO			
0 h	56.74	6.16	13.76 ± 0.15
3 h	56.79	6.24	13.86 ± 0.12
6 h	57.50	6.37	14.07 ± 0.08
9 h	56.63	6.48	14.18 ± 0.27
12 h	57.74	6.51	14.87 ± 0.05
PSO			
0 h	61.85	5.62	11.46 ± 0.48
3 h	57.65	5.46	11.52 ± 0.47
6 h	58.26	5.90	11.71 ± 0.24
9 h	62.19	6.17	12.84 ± 0.49
12 h	54.20	5.73	11.40 ± 0.32
15 h	57.31	5.64	11.71 ± 0.24
18 h	56.67	5.49	11.61 ± 0.24
SO			
0 h	60.60	4.82	11.07 ± 0.11
3 h	60.40	5.15	11.82 ± 0.12
6 h	61.62	5.47	12.46 ± 0.12
9 h	62.19	5.69	13.06 ± 0.06
12 h	61.96	5.58	13.09 ± 0.07
SHO			
0 h	56.29	5.58	11.36 ± 0.21
3 h	56.34	4.62	9.57 ± 0.02
6 h	55.88	4.74	10.28 ± 0.41
9 h	56.41	5.94	12.17 ± 0.25
12 h	61.16	5.14	10.83 ± 0.45
15 h	58.51	4.91	10.44 ± 0.22
18 h	64.21	5.49	11.45 ± 0.24

[a] Average moisture of raw potatoes in the different frying sessions: Vittoria, 81.5 ± 0.2 g/100 g; Bentje, 79.0 ± 0.5 g/100 g.

Fig. 6. Correlation between contact angle and oil uptake calculated for SO.

SHO, respectively. The microstructure of the tuber could in fact depend on the variety, thus affecting potato behaviour during cooking (McComber, Horner, Chamberlin, & Cox, 1994). Actually, a slightly increasing trend of oil uptake was observed only with PO and SO, for which the same potato variety was used ("Vittoria").

For total fat in the fried food, the highest values were observed in French fries cooked in PO according to the highest slip point (ca. 38 °C) and viscosity of the oil that cause a greater oil retention on the surface of food during the cooling step at the end of frying. Consistently, a direct correlation ($p < 0.05$) was found for PO between oil uptake and oil viscosity. However, because an increasing trend was observed for PO uptake as a function of frying time, it can be hypothesized that the oxidative-hydrolytic degradation of PO also has a role in affecting the final oil content of French fries, in addition to the high slip point and viscosity.

4. Conclusions

Contact angle modification of liquid oils proved to be a sound index of overall oil degradation in actual frying experiments, being significantly correlated with common indices of hydrolytic, oxidative, and thermal phenomena. For semi-fluid oils and hard fats the effectiveness of contact angle is, however, limited by the need to carry out the measurement at a temperature above the oil melting point, without perturbing the system.

A significant correlation between contact angle and oil uptake of French fries was found for sunflower oil. For the other frying oils, the importance of factors, such as the structure of food subjected to frying or the oil melting point and viscosity, seem to prevail in influencing potato oil uptake. For instance, the physical characteristics of palm oil mostly account for the highest fat content observed in French fries cooked in this hard fat.

Acknowledgements

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having a slip point of 38 °C (Kochhar, 2001) while, for PSO, which has a slip point below room temperature, between 12.9 and 16.6 °C (Rossell, 2001), a realistic explanation could be a non-equilibrium condition due to the cooling of the oil droplet during measurement. Actually results reported up to now in the literature concern only contact angle measurements of liquid oils at room temperature (Gomes da Silva & Singh, 1995; Michalski et al., 1998; Pinthus & Saguy, 1994).

For SO and SHO, several significant correlations were found between contact angle and the variables signifying the oxidative-hydrolytic status of oils, thus confirming contact angle efficacy as sound index of overall degradation phenomena taking place in the oil during frying. In particular, SHO contact angle was inversely correlated ($p < 0.01$) with oil acidity, PV, total carbonyl compounds, K_{232}, and viscosity, thus indicating that oil degradation during frying causes the formation of polar compounds that ultimately decrease the interfacial tension. The same correlations were found for SO, but at lower significance ($p < 0.05$).

The decrease in the oil–food interfacial tension also accounted for the changes in French fry characteristics (Table 3). In fact, for SO and SHO, potato moisture loss during frying tends to increase with the oil using time. This happens because, as time passes, the oil degradation progress improves the affinity between oil and potatoes, favouring the heat exchange, in agreement with the findings of Blumenthal (1991), and consequently accelerating water evaporation from food. Because oil enters the pores and capillary voids freed from water (Gamble et al., 1987), a correlation should exist between oil uptake and moisture loss. Actually, such correlation was observed for SO ($p < 0.05$) only, as well as the correlation shown in Fig. 6 between oil uptake and contact angle ($p < 0.01$). The absence of similar correlations for SHO could be justified by the use of two different varieties of potatoes for SO and
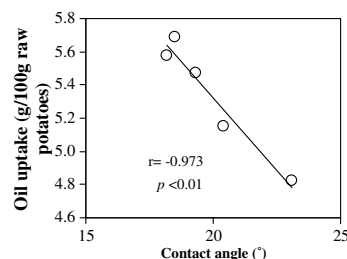
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