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Factors Affecting Oil Uptake in Tortilla Chips in Deep-fat Frying

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ABSTRACT

An understanding of the complex processes that occur during frying is necessary to control the quality of tortilla chips. Quantitative information is needed to describe the rate of oil absorption into the chips during the process. In this study, tortilla chips were processed under different conditions: (1) baking time, (2) frying oil temperature, (3) particle size distribution, and (4) oil quality. The effects of these parameters on the final oil content of tortilla chips were analyzed.

Oil content of tortilla chips was significantly (P <0·05) affected by initial moisture content and particle size distribution. Higher initial moisture content and smaller particle size resulted in higher final oil content. The pore size distribution and/or mass of air developed during frying would result in higher oil content due to high capillary pressure within the pores during cooling.

The final oil content to water removed ratio was independent of frying oil temperature. It was also found that the total final oil content was not affected by oil quality, but the oil distribution was different. Tortilla chips fried in used oil had more oil accumulated at the surface than tortilla chips fried in fresh oil. The higher viscosity and/or lower surface tension of the used oil could cause the oil to adhere to the product's surfaces. Results showed that only 20% of the total final oil content was absorbed by the tortilla chips during frying, and 64% during cooling, leaving only 36% at the chip's surface. © 1997 Elsevier Science Limited

INTRODUCTION

As a food product fries, the internal cells become dehydrated and the evaporated water is partially replaced by the frying oil. The mechanism of oil infiltration is still not fully understood.

Gamble *et al.* (1987a) indicated that as the product fries, the inner moisture is converted to steam, creating a pressure gradient as the surface dries out and causing

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the oil to adhere to the product's surface and enter the surface at damaged areas. They suggested that most of the oil enters the chip from the adhering oil being pulled into the chip when it is removed from the fryer due to a condensation of water vapor in the pores creating a vacuum. Saguy & Pinthus (1995) suggested that as the water is evaporated from the product during frying, the rate of oil absorption increases due to a reduction in the pore internal pressure.

A wide spectrum of factors have been reported to affect oil absorption in fried foods. These include oil quality and composition, frying temperature and time, product composition, moisture content, shape, porosity, pre-frying treatment, surface treatments, initial interfacial tension, and crust size (Gamble & Rice, 1987; Pinthus & Saguy, 1994; Pravisani & Calvelo, 1986; Blumenthal, 1991). Rock-Dudley (1993) noted that as initial moisture content decreased, the final oil content increased in tortilla chips. Gamble & Rice (1988) observed that the regions of the food that were already dried would not allow oil uptake during frying, resulting in larger oil-free zones.

Moreira & Barrufet (1995) simulated the oil distribution in tortilla chips using Monte Carlo simulation. Because of the heterogeneous and complex structure of the porous material, the oil appears to distribute randomly throughout the tortilla chips. This process is explained using percolation theory concepts. By percolation theory the authors simulated the structure of the tortilla chips and the spatial distribution and compositions of its components (oil, water, pores, solid). Since this is a stochastic model, the generated structures would not be alike, however they would mimic what is observed by, for example, MRI techniques. In general, it was shown that most of the oil concentrates in the outer layers of the puffed areas of the chips (Moreira et al., 1995a).

Several researchers tried different approaches to investigate oil distribution in fried products. Gamble et al. (1987b) examined the oil distribution in potato chips, French fries, and extruded snacks using the oil red-stain method. Farkas et al. (1992) and Moreira et al. (1995a) imaged the oil distribution in a cross section area of a potato cylinder and a tortilla chip, respectively, using magnetic resonance imaging (MRI) techniques. McDonough et al. (1993) observed the oil distribution in tortilla chips using environmental scanning electron microscopy (ESEM) techniques. These methods are helpful in understanding the frying processes. However, they still remain post-frying data acquisition. How and when the oil is absorbed into the product is still unknown.

In order to design a frying process for tortilla chips, the effect of process parameters and tortilla chip's initial conditions are needed to predict the final oil content. The objectives of this paper were to determine the amount of oil absorbed during frying and cooling of tortilla chips, and to determine the effect of pre-frying treatments, oil quality, and particle size distribution on the oil absorption of tortilla chips.

MATERIALS AND METHODS

Tortilla chip preparation

Tortilla chips were prepared from nixtamalized dry masa flour for tortilla chips (Tortilla Y1, Valley Grain Products, Muleshoe, TX). The masa flour was mixed with

water (1000 ml/1 kg of dry masa flour) in a pilot scale mixer at low speed for 5 min. The masa was then continuously sheeted and formed into triangular pieces with a commercial sheeter/former (Model CH4-STM, Superior Food Machinery Inc., Pico Rivera, CA), and baked into raw tortilla chips for 70 s in a gas-fired oven with three moving tiers (Model C0400, Superior Food Machinery, Pico Rivera, CA) at 343, 190 and 190°C for the top, middle, and bottom tiers, respectively. The thickness of the tortilla chips was set to 1 mm. Tortilla chips were then deep-fat fried at 190°C for 60 s in a 15-lb capacity batch fryer (Model HK3-2, Hobart, Troy, OH).

Prefrying treatments

The effect of initial moisture content on the final oil content of tortilla chips was analyzed by frying unbaked tortillas, optimum-baked (control sample) tortillas (baked for 70 s), and over-baked tortillas (baked for 140 s) for 60 s at 190°C in fresh soybean oil. The moisture content ranged from 111·28% (d.b.) for the unbaked tortilla to 38·26% (d.b.) for the over-baked one. The optimum-baked tortilla had a moisture content of 78.73% (d.b.).

Frying oil temperature

The effect of frying oil temperature on the final oil content of tortilla chips was determined by frying optimum-baked tortilla chips for 60 s at 130, 160, and 190°C.

Oil quality

The effect of oil degradation on the oil content of tortilla chips was determined by frying optimum-baked tortilla chips in fresh and degraded (1·2% FFA; 66% TPM) soybean oil. In this study, soybean oil was degraded at 190°C by frying 300 g of tortilla chip masa (dough) with 55% (wb) for 10 min at hourly intervals for a total of 50 h. The degradation levels were identified by number of hours the oil was heated during frying. The percentage of free fatty acid (FFA) was determined according to the American Oil Chemists Society method Ca-5a-40 (AOCS, 1989). Total polar materials (TPM) were determined as described in AOAC (1984).

Particle size distribution

To study the effect of particle size distribution of the flour on the final oil content of tortilla chips, the dry masa flour was fractionated into fine, intermediate, and coarse particle sizes by agitating 100-g samples of the flour for 5 min. The fine particles were determined as those which passed through U.S. #100 sieve, inter-mediate particles passed through U.S. #70 sieve but not #100, and coarse particles did not pass through U.S. #70 sieve. The particle size distribution of the dry masa flour consisted of 33·3% fine, 45·3% coarse, and 21·4% intermediate particles.

Sample analysis

Total oil content in the tortilla chips was determined using Soxhlet extraction with petroleum ether (AACC, 1986b). Moisture content in the tortilla chips was deter-mined in a forced air oven at 105°C for 24 h (AACC, 1986a).

Bulk density of tortilla chips was measured using the volume displacement method with amaranth seeds; the true density was determined with a helium gas multi-pycnometer (Quantachrome&trade, NY), and porosity was calculated by $\phi = 1 - \rho_{pB}/\rho_{pT}$ (Moreira et al., 1995b).

Texture of tortilla chips was analyzed using the Texture Analyser^{TM} (TA-XT2, Texture Technology Corp., NY) using a 1/4" diameter ball probe and a 18 mm diameter cylindrical plate. The probe travelled at 2·0 mm/s. The peak force (g), initial slope (g/mm), and work were recorded.

The temperature profile at the center of the chip (thickness of 2 mm) was measured by inserting a thin thermocouple (Type E, 34-gauge-0·01") in the center of the chips. Time–temperature data were recorded during the frying process by a data acquisition system (Model SCXI-100, National Instruments, Austin, TX).

Oil content at the surface and the core of the chips was also measured to determine the oil distribution. The surface oil was washed out by dipping the tortilla chips for 1 s in a 250-ml beaker containing petroleum ether, immediately after frying. The oil dropped in the beaker was collected by evaporating the petroleum ether, and this oil was defined as surface oil content, SOC(% w.b.) = $(W_1/(W_1+W_2)) \times 100$; where W_1 is the weight of oil collected in the beaker (g) and W_2 is the weight of 10 fried chips after the surface oil has been extracted (g). The remaining oil content in the chips (% w.b.) was defined as core oil content and was determined using Soxhlet extraction with petroleum ether (AACC, 1986a).

Data analysis

The data were interpreted by analysis of variance with Duncan's multiple range test on SAS software (SAS, 1985). Statistical significance was expressed at the $P < 0.05$ level. All the measurements made in this study were made at least in triplicate.

Microscopy

Chip samples were mounted on aluminum stubs with conductive adhesive and viewed with no further sample preparation in an Electroscan Model E-3 ESEM (Electroscan Corp., Wilmington, MA) with accelerating voltage of 23 kV. Defatted samples were also mounted on aluminum stubs with conductive adhesive and viewed in the same electron microscope with accelerating voltage of 15 kV.

RESULTS AND DISCUSSION

Oil distribution in tortilla chips

Oil distribution in tortilla chips during frying and cooling is shown in Fig. 1. It was observed that during frying, only 20% of the total oil content (46·7% d.b.) was absorbed by the product, and about 80% of the total oil content remained at the chip's surface. During cooling, about 64% of the total oil content was absorbed by the chips and only 36% remained at the surface. The phenomenon is explained as follows.

During the first 10–15 s of frying, starch gelatinizes, and moisture evaporates at a fast rate resulting in expansion of the capillary pores. During this period, the oil
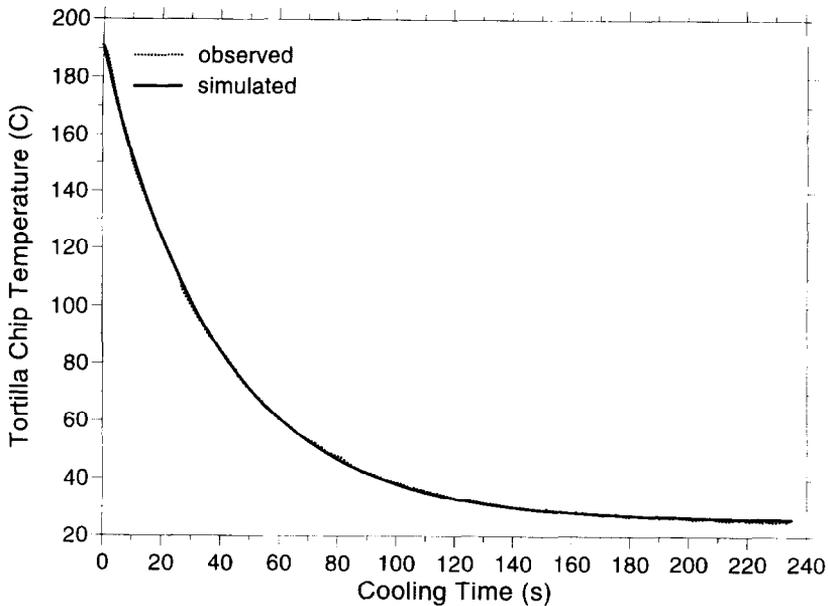
Fig. 1. Temperature history at the center of a tortilla chip during cooling.

adheres to the chip's surface, and flows into the product through the chip's damaged areas. After most of the water evaporates from the chips, temperature in the chips starts to increase and the oil absorption rate reduces due to a decrease in interfacial tension and thus capillary pressure. Once the chip leaves the fryer, its temperature drops, and the pressure within the pore space is reduced. Additionally, the interfacial tension between oil and air increases as temperature decreases and the surface oil starts to flow very rapidly into the porous chip, increasing its internal oil content. Equation (1) shows an expression for capillary pressure in terms of surface forces,

$$P_c = \frac{2(\sigma \cos a)}{r} \tag{1}$$

where P_c = capillary pressure, [Pa]; σ = interfacial tension between liquid and gas, [N/m]; r = inner radius, [m]; α = the contact angle between liquid and surface, [rad]. Using eqn (1), the pressure relationship for a liquid slug in a small vertical tube can be expressed as (Moreira & Barrufet, 1996),

$$P_g = \frac{2(\sigma \cos a)}{r} + \rho_1 gh + P_{atm} \tag{3}$$

where ρ_1 = density of liquid, [kg/m^3]; g = acceleration of gravity, [m/s^2]; h = capillary height, [m]. Figures 1 and 2 show the experimental results of the temperature history of a tortilla chip during cooling, and the oil distribution during frying and
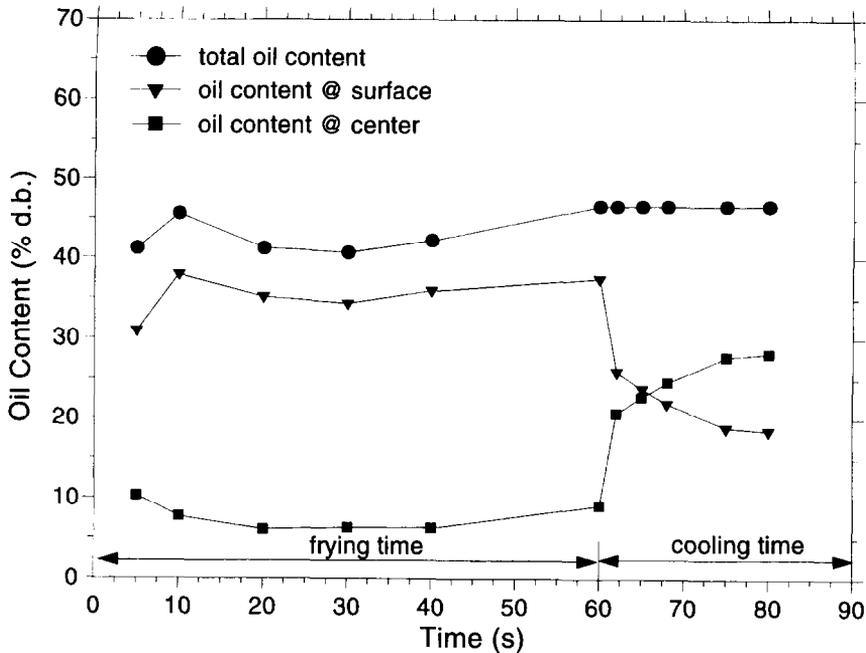
Fig. 2. Oil distribution in tortilla chips during frying and cooling.

cooling, respectively. It takes about 140 s for the center of the tortilla chips to reach 23°C (Fig. 1). As temperature decreases during cooling, the internal oil content increases at a fast rate during the first 15 s of cooling and then slowly thereafter (Fig. 2).

Pre-frying treatments

Table 1 presents the results of baking time on the final oil content of tortilla chips. By increasing the baking time from 0 (unbaked chips) to 140 s (over-baked chips), the initial moisture content of tortilla chips decreased from 111·28 to 38·26% (d.b.), respectively. The tortilla chips were then fried for a constant time of 60 s. Initial moisture content affected significantly ($P<0.05$) the final oil content of the chips (letters A–C).

When using the same frying time, the final moisture content will vary resulting in a different interpretation of the results. Therefore, to eliminate the effect of the final moisture content, it is more reasonable to consider the water removed during frying to compare different treatments (Pinthus et al., 1993). Table 1 shows the relationship between oil uptake ratio (i.e. oil uptake/water removed) and initial moisture content (letters A–C) at different frying temperatures. The oil uptake ratio was significantly ($P<0.05$) affected by the initial moisture content of the chips. Lower initial moisture content resulted in higher oil uptake ratio.

Figure 3 shows the internal oil content profile of tortilla chips under different pre-frying conditions. High initial moisture content resulted in high final oil content.

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TABLE 1

Effects of Frying Oil Temperature, and Baking Time on Final Oil Content of Tortilla Chips
Fried for 60 s

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Samples	Temperature (°C)	Moisture content (% d.b.)		Final oil content (% d.b.)	FOC/MR[1]
		Initial	*Final*		
Unbaked	190 ± 5	111·28 ± 2·84	2·06[A,D]	45·87[A,D]	0·42[A,D]
Optimum-baked	190 ± 5	78·73 ± 3·30	2·98[AB,D]	37·32[B,D]	0·49[B,D]
Over-baked	190 ± 5	38·26 ± 0·80	2·65[AB,D]	29·64[C,D]	0·83[C,D]
Unbaked	160 ± 5	111·28 ± 2·84	4·76[A,DE]	37·58[A,E]	0·35[A,E]
Optimum-baked	160 ± 5	78·73 ± 3·30	4·73[B,DE]	35·63[A,DE]	0·48[B,D]
Over-baked	160 ± 5	38·26 ± 0·80	3·82[C,E]	26·54[B,E]	0·77[C,DE]
Unbaked	130 ± 5	111·28 ± 2·84	31·22[A,F]	34·07[A,F]	0·41[A,D]
Optimum-baked	130 ± 5	78·73 ± 3·30	11·96[B,F]	27·91[B,F]	0·42[AB,E]
Over-baked	130 ± 5	38·26 ± 0·80	7·60[C,F]	24·03[C,EF]	0·78[C,DE]

[1] Final oil content/moisture removed.

[A-F] Averages in the same column within the same data set (category) which are not followed by the same superscript letter are significantly different ($P < 0.05$).

[A-C] Refer to same temperature and different initial moisture content conditions.

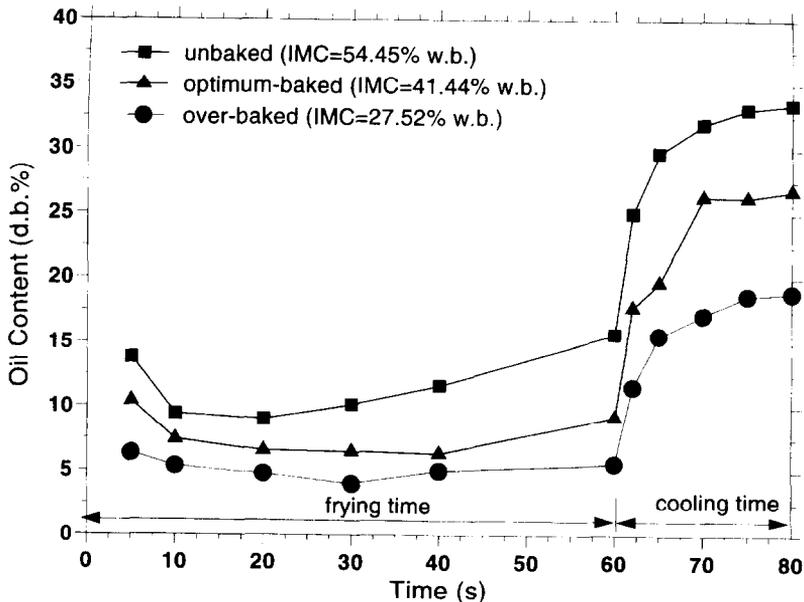[D-F] Correspond to same initial moisture content and different temperature conditions.

Fig. 3. Internal oil content profile for unbaked, optimum-baked and over-baked tortilla chips fried for 60 s at 190°C in fresh soybean oil.

TABLE 2

Peak Force, Initial Slope and Work Values of Unbaked, Optimum Baked and Over-baked Tortilla Chips Fried for 60 s at 190°C (Average of 10 Samples)

Sample	imc (% d.b.)[a]	fmc (% d.b.)[b]	foc (% d.b.)[c]	Peak force (g)	Initial slope (g/mm)	Work (g-mm)
Unbaked	111·28 ± 2·84	2·68% ± 0·22	45·85 ± 2·20	553 ± 57	1674 ± 367	72 ± 30
Optimum-baked	78·73 ± 3·30	2·98 + 0·13	37·32 ± 1·57	691 ± 58	1832 ± 454	115 ± 23
Over-baked	38·26 ± 0·80	2·65 ± 0·14	29·64 ± 1·19	842 ± 52	2302 ± 432	129 ± 32

[a]imc = initial moisture content.
[b]fmc = final moisture content.
[c]foc = final oil content.

The final internal oil content was about 18·98 ± 0·25% (d.b.) for the over-baked, 26·69 ± 0·28% (d.b.) for the optimum-baked, and 32·20 ± 1·42% (d.b.) for the unbaked tortilla chips. Higher initial moisture content can be related to the small pore radius that is formed during frying due to the higher water diffusion rate and/ or lower mass of gas (lower initial porosity). A product with lower initial moisture content and higher initial porosity (more mass of gas) has more tendency to build up pressure within the pores during frying thus causing an enlargement of the pore size resulting in a lower pressure drop for oil absorption during cooling. Higher oil content also results in higher porosity (not shown) indicating that only a fraction of the evaporated water is replaced by the oil in tortilla chips.

Texture tests in these tortilla chips showed as expected that the unbaked tortilla chips had the lowest values of peak force, slope, and work; the over-baked chips had the highest values (Table 2). The structure of the baked chips tends to be harder due to starch gelatinization during baking and frying creating an adhesive-like film matrix ('glue') composed of solubilized starch, denatured protein, lipids, and cell wall materials (Gomez et al., 1992). The simplest and most accurate way of determining 'hardness' of tortilla chips seems to be the peak force. Tortilla chips have irregular shape and size and have an anomalous surface making mechanical measurements more difficult than other homogeneous food products. A minimum of 30 replications is required to obtain reliable results when testing fracturability or hardness of tortilla chips (Moreira et al., 1995b). The use of a combination of acoustic, sensory, and force-deformation tests would give a better judgment of tortilla chip's crispness.

Photomicrographs showed that as the baking time increased, the chips structure became more uniform as starch gelatinized inside the tortilla chips during frying (Fig. 4a–c). The faster rate of water evaporation during frying resulted in smaller pores for the unbaked chip than for the other chips. It seems that the small pores formed during frying trapped more air resulting in a higher capillary pressure during cooling. High capillary pressure resulted in high final oil content after frying [(eqn (1)].

Figure 4d–f shows the effect of pre-frying treatment on oil distribution in the tortilla chips. The absorbed oil was uniformly distributed all over the unbaked chip (Fig. 4d). In the optimum-baked chip, the oil was concentrated at the layers close to the center (Fig. 4e); and it was mostly distributed at the layers closer to the surface

Fig. 4. ESEM of tortilla chips prepared with dry masa flour with different particle size distribution — cross section of defatted samples: (a) fine; (b) intermediate; (c) coarse size; and oil distribution: (d) fine; (e) intermediate; and (f) coarse.

in the over-baked chip leaving larger empty pore spaces at the center (Fig. 4f) due to the low capillary pressure within these pores.

Frying oil temperature

Final oil content and oil temperature relationship (letters D–F) were significantly different ($P < 0.05$) for all treatments; however, the relationship between oil uptake ratio and oil temperature did not exhibit a significant difference ($P < 0.05$) (Table 1). In general, final oil content was more related to the remaining moisture content in the chips than the oil temperature as has been previously reported by Gamble et al. (1987a).

Oil quality

Oil absorption and deterioration increase non-linearly with frying time (Saguy & Pinthus, 1995). A comparison between optimum-baked tortilla chips fried in fresh and degraded (1·2% FFA; 66% TPM) soybean oil showed that more oil was absorbed during cooling by the chips fried in fresh oil (26·8 ± 1·02% d.b.) than for the chips fried in the degraded oil (18·28 ± 0·82% d.b.) (Fig. 5). The total final oil content, however, was roughly the same for the chips fried in the degraded oil (39·18 ± 1·52% d.b.) and for the chips fried in fresh oil (41·55 ± 1·95% d.b.). Most of the oil absorbed by the chips fried in degraded was oil concentrated at the surface. The higher viscosity and/or lower surface tension of the used oil could cause it to
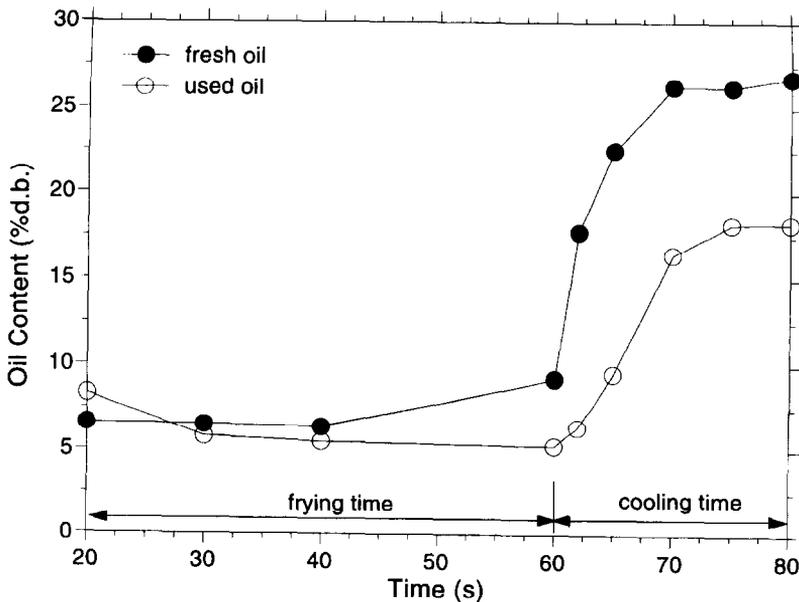

Fig. 5. Internal oil content history in tortilla chips fried in fresh and used oil for 60 s at 190°C.

adhere to the product's surfaces thus making it more difficult for the oil to be washed off from the chip's surface and/or to flow into the center of the chip during cooling. Tseng *et al.* (1995) observed that viscosity values between fresh and 60-h degraded soybean oil (FFA = 0·61%, TPM = 61·54%) increased from $5·32 \times 10^{-2}$ to $2·08 \times 10^{-1}$ Pa.s at 25°C, and from $2·04 \times 10^{-3}$ to $4·39 \times 10^{-3}$ Pa.s at 190°C; and surface tension decreased from 30·14 to 27·49 dyne/cm at 25°C.

Particle size distribution

Tortilla chips prepared from finely ground masa showed excessive puffing and pillowing, resulting in higher oil absorption and lower porosity; tortilla chips made from coarse particles, presented the lowest oil content and no puffing; and intermediate masa produced tortilla chips with final oil content closer to the control sample (Table 3). Final oil content to water removed ratio was lower for tortilla chips made from coarse flour than from fine flour.

The fine particles in the masa are responsible for most of the water uptake and viscosity development during mixing (Gomez *et al.*, 1987). The function of the coarse particles is to produce fissures in the product that allow water to escape during frying and reduce oil absorption during cooling, and to reduce the extent of pillowing during baking and frying. Therefore, a moderately coarse masa is desirable for fried corn snacks.

Figure 6a–f shows the photomicrographs (cross sections) of tortilla chips prepared from different particle size dry masa flours. Tortilla chips made from fine masa (Fig. 6a) contained numerous small pores closer to the surface and few larger pores in the interior. Most of the oil filled the pores within the chips (Fig. 6d). Cross-sections of tortilla chips prepared from intermediate particle size flour (Fig. 6b,e) produced larger and deeper pores than the tortilla chips made from fine masa. Most of the pores were filled with the frying oil. Coarse masa resulted in the formation of large pores within the tortilla chips (Fig. 6c). The oil filled some pores but left many of then empty (Fig. 6f) due to a decrease in capillary pressure within the larger pores.

TABLE 3
Oil Content, Porosity, and Bulk Density of Tortilla Chips as a Function of Particle Size Distribution

Sample	Final oil content (% d.b.)	Moisture content (% d.b.)		Porosity	Bulk density (kg/m³)	FOC/MR
		Initial	Final			
100% fine	45·97 + 0·36	60·26 + 1·48	1·39 + 0·18	0·49	717 + 20	0·78
100% intermediate	31·30 + 0·05	59·01 + 1·52	0·97 + 0·09	0·60	603 + 58	0·54
100% coarse	27·73 + 0·40	59·13 + 1·27	1·01 + 0·07	0·56	652 + 43	0·48
Control sample (33·3% fine, 21·4% intermediate, 45·3% coarse)	33·97 + 0·26	62·23 + 2·28	1·29 + 0·05	0·57	662 + 26	0·56

Tortilla chips were optimum baked and fried in fresh oil for 60 s at 190°C.
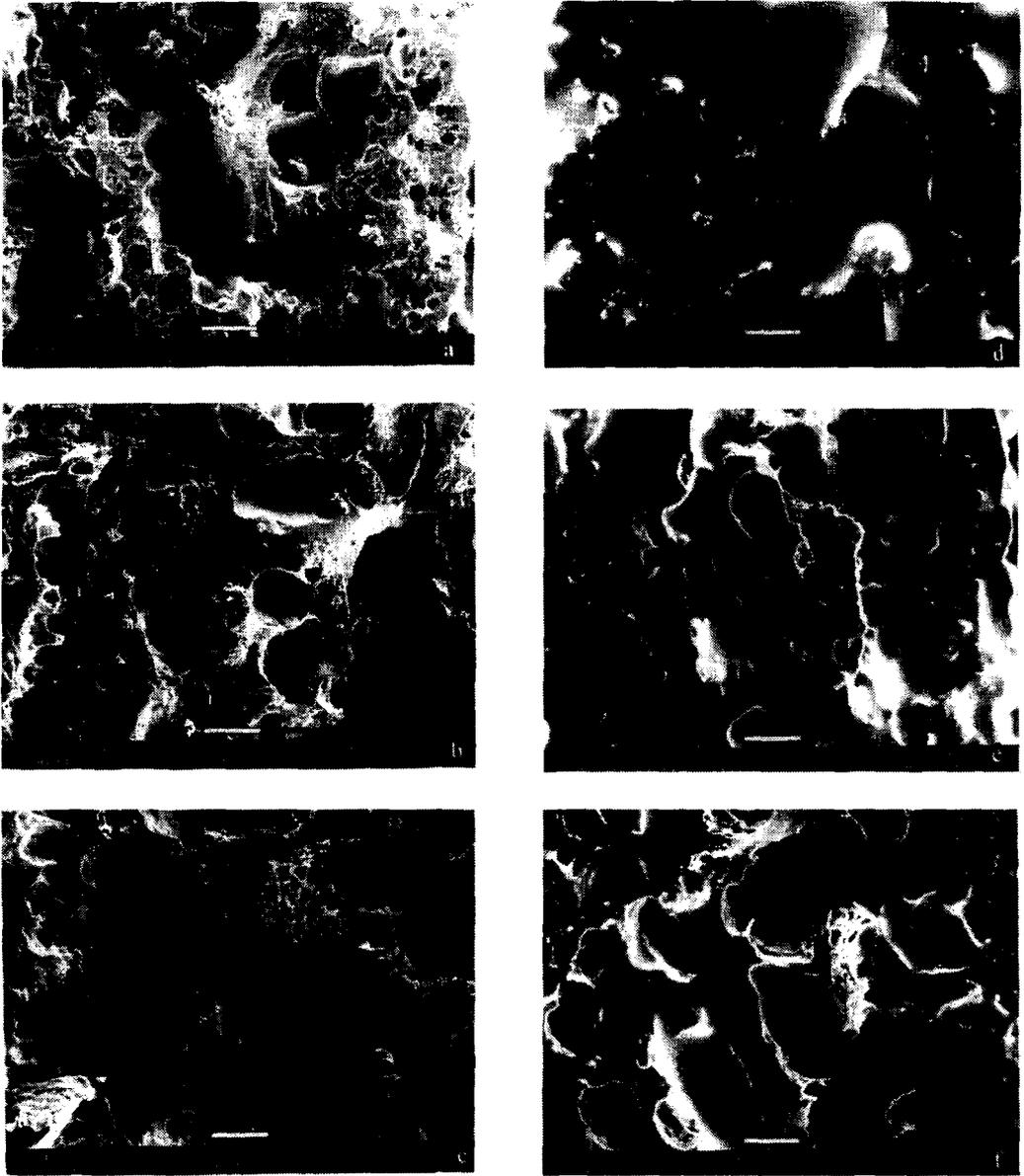
Fig. 6. ESEM — cross section of defatted samples: (a) unbaked; (b) optimum-baked (for 70 s); (c) over-baked (for 140 s); and oil distribution: (d) unbaked; (e) optimum-baked; and (f) over-baked.

Relating oil absorption to initial moisture content, oil temperature, particle size distribution

Based on the experimental results, regression equations were calculated for the averaged values of all conditions. The derived equations are given below:

$$\text{FOC} = 16.588 + (0.00275302 * T - 0.3004) * \text{IMC} + 0.14848 * \text{FP} \ (R^2 = 0.86) \tag{3}$$

$$\text{FOC/MR} = 0.834 - 10.005 * \text{IMC} + 0.0044 * \text{FP} - 1.604 \times 10^{-5} * \text{FP}^2 \ (R^2 = 0.89)$$

where FOC = final oil content (%d.b.) of tortilla chips, MR = moisture removed (%d.b.), T = oil temperature (°C), IMC = initial moisture content (%d.b.) of tortilla chips, FP = % of fine particles in the dry masa flour.

CONCLUSIONS

The effects of pre-frying treatment, oil temperature, oil quality, and particle size distribution on the final oil content of tortilla chips were analyzed.

Tortilla chips absorbed only 20% of the total final oil content during frying, and 64% was absorbed during cooling leaving only 36% at the chip's surface.

Initial moisture content significantly affected the final oil content of tortilla chips; as initial moisture content increased the final oil content increased. As the initial moisture content decreased, the force to break the chips increased. Scanning electron micrographs showed that pore size distribution developed during frying is the main cause for oil absorption during cooling. Small pores trapped more air during frying resulting in a higher capillary pressure during cooling and then higher final oil content.

Oil content to water removed ratio was not significantly ($P < 0.05$) affected by frying oil temperature in the range of 130–190°C.

The amount of oil absorbed was related to particle size distribution in the dry masa flour. A coarse flour produces tortilla chips with lower oil content than fine masa flour.

Although the total final oil content was not significantly affected by the oil quality, tortilla chips fried in fresh oil have less oil concentrated at the surface than tortilla chips fried in used oil.

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