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ORIGINAL PAPER

Kinetics of Mass Transfer in Microwave Precooked and Deep-Fat Fried Ostrich Meat Plates

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Abstract The aim of this study was to evaluate the effect of microwave precooking on mass transfer during deep-fat frying of ostrich meat plates. The influence of microwave power level, frying temperature, and time on mass transfer was determined. Among all treatments, the plates being precooked at 5.23 W/g of microwave power and then deep-fat fried at 135 °C had the minimum fat content. The effective moisture diffusivity ranged between 1.47×10^{-8} and 4.17×10^{-8} m^2/s. Fat transfer rate constant was in the range of 0.024 and 19.708 s^{-1}. The activation energy obtained from Arrhenius plot for the effective moisture diffusivity ranged between 38.84 and 51.07 kJ/mol.

Keywords Deep-fat frying · Microwave precooking · Ostrich meat · Mass transfer

Nomenclature

M	Moisture content (g/g, db)
M_e	Equilibrium moisture content (g/g, db)
M_0	Initial moisture content (g/g, db)
M_r	Moisture ratio, dimensionless
ML	Moisture loss (g/g)
L	Half thickness of the sample (m)
k	Rate constant (s^{-1})
D_{eff}	Effective diffusivity (m^2/s)
D_0	Effective diffusivity at high liquid concentration (m^2/s)
t	Time (s)
FC	Fat content (g/g)
FU	Fat uptake (g/g)
C_0	Equilibrium fat content (g/g)
R	Universal gas constant (0.0083143 kJ/mol K)
E_a	Activation energy (kJ/mol)
T	Absolute temperature (K)

Greek Symbol

π Pi (22/7)

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Introduction

Production of ostrich (*Struthio camelus*) was initially developed in South Africa for feather production and later for leather. However, ostriches have been raised on other countries around the world for meat production (Balog and Almeida Paz 2007). At 14 months of age, an ostrich can yield 34–41 kg of low fat, red meat. On an ostrich carcass of 55 kg, 62.5% consists of separable lean meat with 15% of fat content. Each bird has 10–20 kg of exportable meat, primarily from the legs, in a ratio of 66% steaks to 33% fillets. Meat cuts of a high commercial value reach as high as 80–90% in the ostrich compared to approximately 45% in other species. Ostrich meat may be marketed in a variety of forms for which demand must be carefully established: steaks and fillets, processed forms (kebabs, hamburger patties, smoked, biltong, cold meats, sausage, hotdog, and mincemeat), stews (the neck), tinned foods (ostrich meat/vegetable mix, meat mixes, and soups), and pet food (dirty offal). Some beef producers have switched to raising ostriches commercially because of the higher and faster financial returns (Hallam 1992; Jones et al. 1995; Smith et al. 1995; Cooper 1999).

The development of this sector opens the market for ostrich meat while one of its attractive characteristics is its novelty (Balog and Almeida Paz 2007). Ostrich meat is perceived and marketed as a healthy alternative to other red meats. Compared to beef, ostrich meat is characterized by a higher ultimate pH (>6.2), lower collagen and higher pigment content, darker visual appearance, similar cooking loss and sensory tenderness, lower fat content, and favorable fatty acid profile, with an emphasis on high polyunsaturated fatty acid content (Lanza et al. 2004; Fernández-López et al. 2006).

Deep-fat frying is extensively used in fast food restaurant chains as well as at household levels. The process yields desirable product characteristics such as crispiness, appealing flavor, and color in a relatively short cooking time (Ngadi et al. 2006). It is a unit operation which is mainly used to alter the eating quality of a food. Deep-fat frying is a multifunctional operation of food transformation. This process may be defined as cooking food by immersion in edible oil or fat at a temperature above the boiling point of water (Hubbard and Farkas 2000). It is a rapid process of simultaneous heat and mass transfers, which can be used as a drying operation. During this kind of cooking process, oil is used both as the heating medium and as an ingredient producing calorific products (Ziaiifar et al. 2008).

Microwave heating has many advantages such as energy saving, shorter cooking/warming times, improved product uniformity, and yielding of unique microstructures and properties. Microwave heating is greatly affected by the presence of water in foods. There is uniform heating of the product leading to moisture evaporation during microwave heating. There is no information on moisture loss and fat uptake of deep-fat fried meats pretreated in microwave oven. It is expected that the high initial moisture content of the meats will allow quick heating in the microwave oven due to the interaction between the dipole of the water molecules and the microwave environment (Ngadi et al. 2009). Adedeji et al. (2009) and also Ngadi et al. (2009) have perused the effect of microwave pretreatment on mass transfer during deep-fat frying of chicken nuggets.

Although frying is a common process, researches about engineering aspects are limited. While the snack foods, such as potatoes (chips and French fries) or tortilla chips, are the most studied fried products, information about kinetics of mass transfer in fried meat products is scarce (Sosa-Morales et al. 2006).

There is no scientific literature about frying of ostrich plates. Therefore, the present study aimed to obtain moisture diffusion coefficients and fat uptake kinetics coefficients during deep-fat frying of ostrich meat plates. The results of this study can be applied in optimizing the process of ostrich meat frying.

Modeling

In deep-fat frying, moisture transfer is considered as diffusion controlled. The moisture transfer phenomenon can be described by the Fick's second law of diffusion (Sosa-Morales et al. 2006; Adedeji et al. 2009), as expressed by

$$\frac{\partial}{\partial L}\left[D_{\mathrm{eff}}\frac{\partial M}{\partial L}\right]=\frac{\partial(M)}{\partial t} \tag{1}$$

If initial moisture content remains constant, possible shrinkage and external resistance to mass transfer assume insignificant, and mass transfer occurred from both sides of the fried products, solution of partial differential Eq. 1 was demonstrated by Crank (1975) as follows:

$$M_{\mathrm{r}}=\frac{M-M_{\mathrm{e}}}{M_0-M_{\mathrm{e}}}=\frac{8}{\pi}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\pi^2\frac{D_{\mathrm{eff}}t}{4L^2}\right] \tag{2}$$

Equation 2 can be abridged as follows when M_{e} is very small:

$$M_{\mathrm{r}}=\frac{M}{M_0}=\frac{8}{\pi}\exp\left(-\frac{\pi^2 D_{\mathrm{eff}}t}{4L^2}\right)=\frac{8}{\pi}\exp(-kt) \tag{3}$$

The Fick's law of diffusion has been widely used to describe the water loss kinetics during frying (Yildiz and Dincer 1995; Moreira et al. 1997; William and Mittal 1999; Mittal and Zhang 2000). It provides a simplified picture of the water loss during frying.

For fat uptake modeling, a first order kinetic model suggested by Krokida et al. (2000) was considered:

$$\mathrm{FC}=C_0[1-\exp(-kt)] \tag{4}$$

Temperature dependency of diffusivity can be determined using the Arrhenius expression:

$$D_{\mathrm{eff}}=D_0\exp\left[-\frac{E_{\mathrm{a}}}{RT}\right] \tag{5}$$

Materials and Methods

Sample Preparation

Ostrich fillet obtained from the leg muscle of Blue Neck (*Struthio camelus australis*) ostriches was purchased from an abattoir in Mashhad, Iran. Frozen meat was cut in plates of about 25×20×13 mm using an industrial dicer (Food

Table 1 Mean squares from the analysis of variance of the ML and FU

Source	Degree of freedom	ML	FU
A	2	0.108707**	0.0076153**
B	3	0.016179**	0.0001359 NS
R (A, B)	24	0.000697	0.0006489
C	8	0.113405**	0.0039060**
A × B	6	0.005776**	0.0017973*
A × C	16	0.006263**	0.0018155**
B × C	24	0.001965**	0.0006785**
Error	240	0.000130	0.0000430
Total	323		

ML moisture loss, *FU* fat uptake, *A* temperature, *B* microwave power, *C* time, *R* replication, *NS* not significant

* p=0.05; ** p=0.01

logistic, MF 84, Germany) and covered with plastic film to avoid surface dehydration.

Ostrich meat plates were kept at frozen temperature (−18 °C) before the experiments. The samples were thawed by refrigeration (at 4 °C) for 24 h prior to processing. Thawed meat plates were precooked in a calibrated kitchen microwave oven (2,450 MHz, S4821, Boutan, Iran) at three microwave power densities, 5.23, 10.47, and 15.70 W/g for 30 s. Three samples were placed in the system for each batch. Frying was carried out in a deep-fat fryer (Delonghi F17233) with a capacity for 2 L. One hundred percent pure sunflower oil (Shadgol, Nishapur, Iran) was employed as frying medium. A batch size of 80 g of meat plates in 2 L of oil was selected for further processing. Samples were placed in a wire basket to ensure good contact between samples and the oil. The unprecooked and precooked meat plates were fried at nine intervals between 0 and 135 s at three temperatures (135, 150, and 160 °C). The oil was preheated for an hour at these temperatures prior to frying. Meat plates were immediately blotted with paper towel after frying to remove surface oil. After each frying test, oil level was checked and replenished; oil was changed after 1 h of frying time.

Experimental Analysis

Moisture content (dry basis) was determined by drying the fried samples in an oven (Memmert, Beschickung-loading, model 100-800) at 105 °C for 24 h (AOAC 1990). For fat determination, the dried samples were ground in a mortar. About 2 g of the samples were weighed into thimbles for solvent extraction.

Fat extraction was carried out with petroleum ether (b.p. 40–60 °C) using a Soxhlet Extractor following the protocol recommended by AOAC Method 960.39 (AOAC 1990), and the oil content was reported on dry weight basis.

Statistical Analysis

Analysis of variance was carried out for data analysis using Minitab Release 15 (Minitab Inc., State College, PA). The experimental design was a split-plot on frying temperature and microwave precooking. The level of statistical significance was determined at 95% probability. All experiments were run in triplicate.

Table 2 Means of moisture content (MC; dry basis) during deep-fat frying of ostrich meat plates at different microwave power (watts per gram), temperatures (degrees Celsius), and frying times (second)

Microwave power (W/g)	Temperature (°C)	MC (db)								
		15s	30s	45s	60s	75s	90s	105s	120s	135s
0	135	3.03	2.77	2.59	2.58	2.67	2.03	2.13	2.04	2.06
	150	3.17	2.64	2.36	2.23	2.31	1.78	1.85	1.75	1.63
	160	2.78	2.56	2.00	1.90	1.83	1.54	1.43	1.49	1.24
5.23	135	2.87	3.03	2.67	2.57	2.42	2.27	2.16	2.03	2.19
	150	2.93	2.39	2.29	2.16	2.00	1.82	1.90	1.71	1.56
	160	2.85	2.49	2.10	2.09	1.75	1.71	1.58	1.68	1.28
10.47	135	2.42	2.83	2.37	2.17	2.13	2.03	1.91	1.91	1.65
	150	2.85	2.72	2.57	1.96	1.82	1.74	1.97	1.64	1.50
	160	2.86	2.57	2.06	1.80	1.49	1.54	1.56	1.53	1.13
15.7	135	2.48	2.50	2.24	2.03	1.93	1.80	2.03	2.14	1.84
	150	2.52	2.15	1.97	1.82	1.64	1.57	1.70	1.75	1.39
	160	2.80	2.47	2.12	2.02	1.61	1.57	1.59	1.76	1.22

Table 3 Standard deviations (SD) of moisture content (MC; dry basis) during deep-fat frying of ostrich meat plates at different microwave power (watts per gram), temperatures (degrees Celsius), and frying times (second)

Microwave power (W/g)	Temperature (°C)	SD of MC (db)								
		15s	30s	45s	60s	75s	90s	105s	120s	135s
0	135	0.01	0.2	0.1	0.17	0.01	0.03	0.18	0.16	0.19
	150	0.05	0.07	0.09	0.06	0.06	0.03	0	0.06	0.03
	160	0.07	0.06	0.06	0.06	0.04	0.02	0.08	0.08	0.06
5.23	135	0.12	0.15	0.12	0.02	0.12	0.06	0.21	0.1	0.1
	150	0.11	0.06	0.14	0.04	0.09	0.09	0.05	0.04	0.07
	160	0.1	0.01	0.02	0.11	0.01	0.06	0.07	0.08	0.06
10.47	135	0.18	0.19	0.12	0.11	0.07	0.07	0.14	0.07	0.07
	150	0.07	0.13	0.01	0	0.11	0.04	0.03	0.04	0.01
	160	0.06	0.11	0.07	0.06	0.06	0.06	0.02	0.05	0.03
15.7	135	0.24	0.23	0.15	0.07	0.06	0.11	0.13	0.06	0.11
	150	0.21	0.07	0.07	0.05	0.07	0.07	0.09	0.08	0.09
	160	0.18	0.18	0.08	0.03	0.05	0.07	0.03	0.09	0.01

Results and Discussion

Moisture Loss and Fat Uptake

Initial moisture content of ostrich meat was found to be 3.24±0.20 on dry basis (AOAC 1990).

The main effect of temperature, microwave, time, and interaction between treatments were significant ($P<0.05$) on moisture loss. In Table 1, parts of ANOVA tables for water loss and fat uptake of fried samples are given.

The calculated mean moisture and fat content of fried ostrich meat plates, in addition to the standard deviation, as a function of frying time for unprecooked samples and microwave precooked samples are presented in Tables 2, 3, 4, and 5.

Changes in moisture content of deep-fat fried ostrich meat plates for unprecooked samples and samples which are precooked at 5.23 W/g of microwave power are depicted in Figs. 1 and 2. The same trends were observed under other frying conditions.

Rapid decreasing can be seen in moisture loss in the first minute of frying. Similar pattern is reported by Balasubramaniam et al. (1997) for chicken nuggets.

Moisture content was significantly influenced by the power density of microwave precooking. There was an

Table 4 Means of fat content (FC; dry basis) during deep-fat frying of ostrich meat plates at different microwave power (watts per gram), temperatures (degrees Celsius), and frying times (second)

Microwave power (W/g)	Temperature (°C)	FC (db)								
		15s	30s	45s	60s	75s	90s	105s	120s	135s
0	135	0.10	0.10	0.08	0.10	0.09	0.11	0.10	0.11	0.09
	150	0.09	0.09	0.09	0.11	0.09	0.09	0.10	0.12	0.12
	160	0.06	0.07	0.08	0.10	0.11	0.11	0.13	0.14	0.13
5.23	135	0.08	0.08	0.08	0.09	0.07	0.10	0.09	0.09	0.07
	150	0.09	0.08	0.09	0.11	0.08	0.08	0.09	0.10	0.10
	160	0.09	0.09	0.11	0.13	0.12	0.12	0.15	0.14	0.15
10.47	135	0.11	0.09	0.11	0.09	0.10	0.09	0.09	0.10	0.13
	150	0.08	0.09	0.11	0.10	0.09	0.07	0.09	0.10	0.14
	160	0.07	0.08	0.10	0.11	0.13	0.09	0.11	0.12	0.15
15.7	135	0.10	0.08	0.09	0.10	0.08	0.11	0.09	0.08	0.10
	150	0.10	0.10	0.11	0.10	0.11	0.10	0.11	0.10	0.12
	160	0.09	0.08	0.09	0.11	0.12	0.12	0.13	0.11	0.13

Table 5 Standard deviations (SD) of fat content (FC; dry basis) during deep-fat frying of ostrich meat plates at different microwave power (watts per gram), temperatures (degrees Celsius), and frying times (second)

Microwave power (W/g)	Temperature (°C)	SD of FC (db)								
		15s	30s	45s	60s	75s	90s	105s	120s	135s
0	135	0.002	0.008	0.005	0.013	0.007	0.007	0.008	0.011	0
	150	0.016	0.009	0.014	0.011	0	0.006	0.005	0.005	0.007
	160	0.008	0.008	0.013	0.006	0.015	0.009	0.011	0.005	0.014
5.23	135	0.008	0.012	0.003	0.007	0.005	0.018	0.002	0.012	0.002
	150	0.011	0.003	0.005	0.008	0.001	0.018	0.011	0.014	0.015
	160	0.006	0.007	0.008	0.003	0.009	0.012	0	0.01	0.009
10.47	135	0.011	0.002	0.013	0.01	0.013	0.009	0.01	0.006	0.013
	150	0.016	0.006	0.008	0.015	0.004	0.012	0.007	0.003	0.007
	160	0.005	0.006	0.017	0.009	0.005	0.001	0.011	0.016	0.007
15.7	135	0.014	0.01	0.007	0.014	0.017	0.006	0.008	0.01	0.01
	150	0.014	0.007	0.015	0.01	0.009	0.009	0.011	0.016	0.013
	160	0.008	0.01	0.02	0.001	0.014	0.002	0.016	0.009	0.016

initial reduction in moisture content due to microwave precooking as shown in Fig. 3 for a temperature of 135 °C.

Moisture content in ostrich meat reduced from an initial value of 3.24 (grams per grams, dry basis) to 3.08, 3.00, and 2.91 (grams per grams, dry basis) after precooking with the microwave power densities of 5.23, 10.47, and 15.70 W/g, respectively. As expected, samples with higher initial moisture before frying generally had higher final moisture. This is due to the ease of removing free water and the application of energy for moisture evaporation during the frying process. Increasing power density decreased initial moisture content and subsequently decreased the final moisture content of samples after frying.

Figure 4 shows the fat absorption profile for the unprecooked and precooked ostrich meat plates fried at 160 °C.

The effect of frying temperature on final oil content of fried product is contradictory in literature. Our results showed that high temperatures lead to more oil content in ostrich meat plates, especially after 45 s of frying. During frying at high temperatures, oil absorption takes place during the frying period leading to more oil content. Similar results have reported by Gamble et al. (1987) for potato slices, Moreira et al. (1995) for tortilla chips, and Vélez-Ruiz et al. (2002) for chicken strips.

Figures 5 and 6 show a partially sensible rebate in oil content of ostrich meat plates after precooking in the microwave prior to frying.

Except for the main effect of microwave power, fat transfer was significantly affected by the main effect of temperature, time, and interaction between time and temperature.

There was a sudden increase in the fat content of ostrich meat plates after 30 s of frying. Ngadi et al. (2006) and Adedeji et al. (2009) also observed similar timing for frying of chicken nuggets. Unprecooked samples showed a gradual increase in fat content with frying, but fat

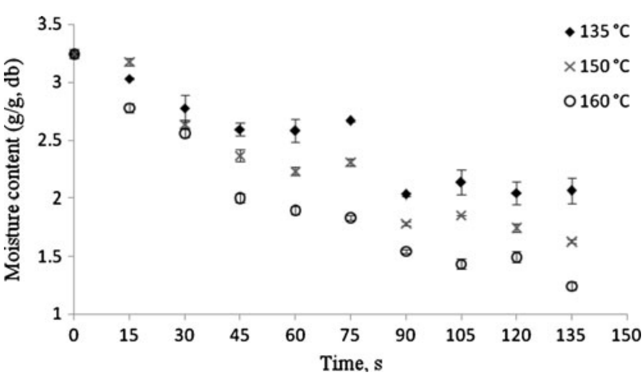

Fig. 1 Temperature effect on mean moisture change in unprecooked samples

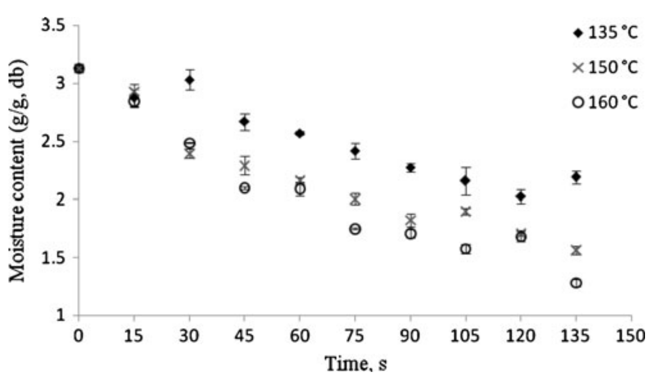

Fig. 2 Temperature effect on mean moisture change in microwave precooked samples (5.23 W/g)

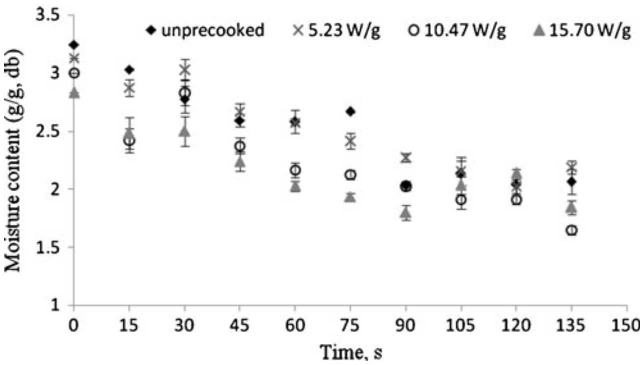

Fig. 3 Effect of microwave precooking at different power densities on moisture content of ostrich meat plates fried at 135 °C

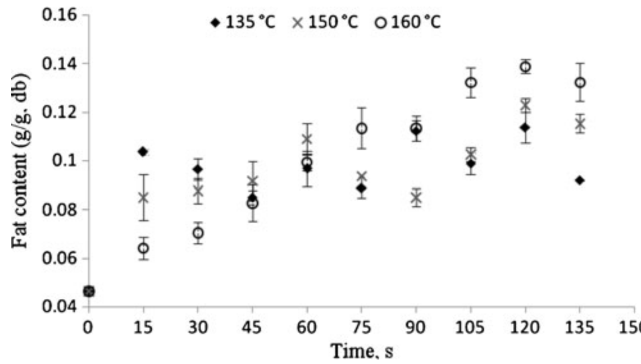

Fig. 5 Effect of temperature on fat content of ostrich meat plates in unprecooked samples

absorption in precooked ostrich meat plates changed significantly with frying time especially in 75 s.

There was a furious surface boiling in the first 90 s of frying, demonstrating moisture evaporation pattern from within the food material into the oil and oil penetration into the product. This subsided after the moisture content of the product has reduced significantly. Similar result was also reported by Mai Tran et al. (2007) for pre-dried deep-fat fried potato crisp.

Diffusion Modeling

The experimental moisture content data was fitted to the exponential model (Eq. 3). A nonlinear regression approach was used to estimate best fit moisture diffusivity. Effective moisture diffusivity was determined from the rate constant, *k*, as given below:

$$D_{\text{eff}} = \frac{4kL^2}{\pi^2} \tag{6}$$

where L is the half thickness of the meat samples since moisture is assumed to migrate from both surfaces.

Diffusion theory assumes that liquid moves through a solid body as the result of a concentration gradient. 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. For materials with weak structure due to high water content and/or due to the absence of cell structure, liquid water transport can be so intense that liquid water escapes from the product surface without vaporization (Sahin and Sumnu 2009).

The model parameters for moisture diffusion in ostrich meat plates are shown in Table 6 and Fig. 7. The effective moisture diffusivity ranged between 1.47×10^{-8} and 4.17×10^{-8} m^2/s with R^2 between 0.68 and 0.97. Effective moisture diffusivities increased with temperature, but the most moisture diffusivity accorded in 10.47 W/g of microwave power density, and the least one was seen in 15.70 W/g of microwave power density. The differences observed in the moisture diffusivities could be due to the effect of microwave precooking.

These values were higher than the values reported by Ngadi et al. (2006) and Adedeji et al. (2009) for chicken nuggets, but they are within the range of 1.59×10^{-9} to 3.02×10^{-8} m^2/s estimated by Sosa-Morales et al. (2006) for pork meat plates fried between 90 and 110 °C.

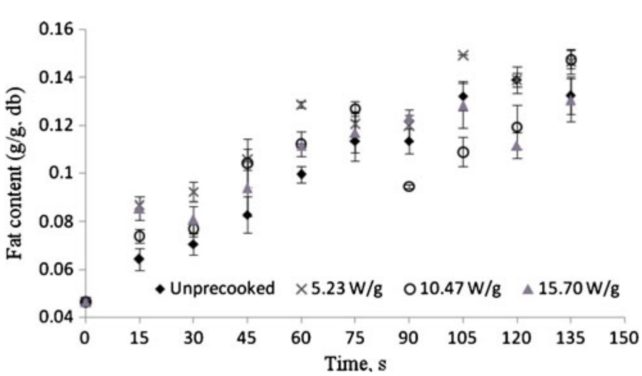

Fig. 4 Effect of microwave precooking on fat content of ostrich meat plates fried at 160 °C

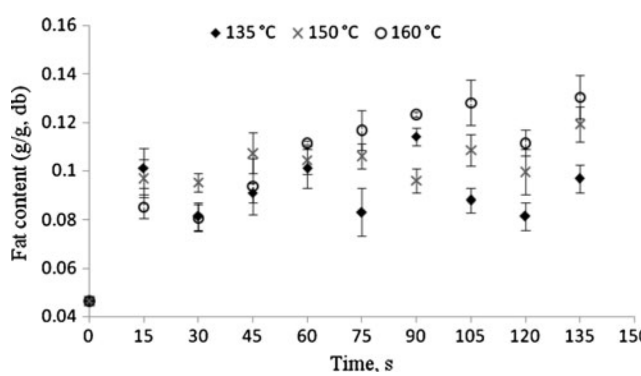

Fig. 6 Effect of temperature on fat content of ostrich meat plates precooked at 15.70 W/g of power density

Table 6 Model parameters for moisture transfer in ostrich meat plates

Microwave power (W/g)	Temperature (°C)	$k\times10^{-3}$ (s^{-1})	$D_{eff}\times10^{-8}$ (m^2/s)	R^2
0[a]	135	1.03	1.84	0.88
	150	1.60	2.86	0.95
	160	2.27	4.07	0.97
5.23	135	0.91	1.63	0.92
	150	1.51	2.71	0.97
	160	1.98	3.55	0.94
10.47	135	1.19	2.13	0.91
	150	1.67	2.99	0.90
	160	2.33	4.17	0.90
15.70	135	0.82	1.47	0.68
	150	1.48	2.66	0.84
	160	1.94	3.47	0.87

[a] Unprecooked samples

Fitting Eq. 4 to fat absorption data using SlideWrite Plus 2.0 (Advanced Graphic Software Inc., Landbouw Univ. Wageningen) gave rate constant, k, values ranging from 0.024 to 19.708 s^{-1} (Table 7).

The rate constant increased with increasing microwave power level and decreasing the temperature. There was a very large difference between the values of fat absorption rate constants obtained in this study for the control untreated samples (0.024–2.855 s^{-1}) compared to the values for microwave pretreated samples (0.044–19.708 s^{-1}). Durán et al. (2007) reported rate constant in the range of 0.18–2.00 s^{-1} for pre-treated potato chips that were fried between 120 and 180 °C. Moreira et al. (1995) reported a k range of 0.22–0.33 s^{-1} for tortilla chips fried between 150 and 190 °C, while Adedeji et al. (2009) presented a range of 0.09–40.96 s^{-1} for microwave precooked chicken nuggets that were fried between 170 and 190 °C.

The type of product, pretreatments applied, and frying conditions are important parameters that determine fat

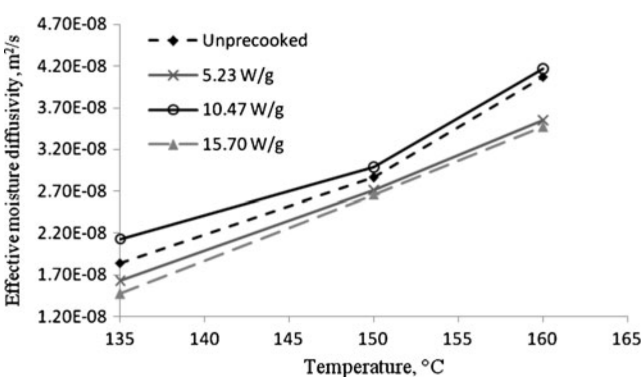

Fig. 7 Effective moisture diffusivity of ostrich meat plates during frying in different temperatures

Table 7 Rate constants for fat uptake in ostrich meat plates during frying

Temperature (°C)	Rate constant, k, for oil transfer during frying (s^{-1})			
	0W/g[a]	5.23W/g	10.47W/g	15.70W/g
135	2.855 (0.75)	0.243 (0.70)	8.306 (0.74)	19.708 (0.72)
150	0.099 (0.74)	0.172 (0.73)	0.116 (0.64)	0.160 (0.80)
160	0.024 (0.86)	0.044 (0.84)	0.045 (0.77)	0.050 (0.81)

Numbers in parenthesis are coefficient of determination, R^2

[a] Unprecooked samples

absorption rate constants. Data on fat absorption rate constants for ostrich meat are not available in the literature. The values obtained for control samples were close to the ranges reported by other authors for different products. However, microwave pretreatment apparently changed the structure of the ostrich meat plate, which considerably resulted in the changes in rate constants.

The temperature dependency of the effective diffusivity coefficient for moisture and oil is shown by the Arrhenius expression (Eq. 5; Table 8). The natural logarithm of the effective diffusivity was plotted against the reciprocal of the absolute temperature. The slope is equal to the ratio of activation energy and the universal gas constant.

Activation energy for the effective moisture diffusivity ranged between 38.84 and 51.07 kJ/mol. A range between 34 and 54 kJ/mol was presented by Motarjemi (1989) for moisture diffusion during oven frying of minced meat. Budžaki and Šeruga (2005) also reported activation energy of 30 kJ/mol for moisture transfer in deep-fat frying of “Kroštula” dough. The R^2 values show a good prediction (Table 8).

Conclusion

Deep-fat frying remains a complex operation because of the two mass transfers in opposite directions within the material

Table 8 Computed activation energy and R^2 values for ostrich meat plates

Power density (W/g)	MC		FC	
	E_a (kJ/mol)	R^2	E_a (kJ/mol)	R^2
0[a]	46.26	0.99	284.71	0.99
5.23	46.03	0.99	94.28	0.80
10.47	38.84	0.98	316.16	0.95
15.70	51.07	0.99	361.45	0.96

MC moisture content, *FC* fat content

[a] Unprecooked samples

being fried. Additionally, oil uptake is a complex phenomenon resulting from interactions between oil and products that undergo numerous physical, chemical, and structural transformations during frying. In the ostrich meat frying, precooking with microwave at different power densities resulted in higher oil uptake while reduced moisture content of the product generally. Precooking causes structural changes in the product, and composition of food plays considerable part in pore development. Paradoxical results about the effect of microwave precooking are cited in the literature. While lower oil uptakes were observed in fried potatoes, higher oil contents were reported in microwave fried chicken fingers in comparison with traditional deep-fat frying. The results of this research can be attributed to the pore formations during microwave precooking. In order to satisfy the nutritional considerations of consumers based on the results of this study, optimization of ostrich meat frying can be carried out by introducing a new term: moisture loss to fat uptake which may be used as objective function mathematically.

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References

Adedeji, A. A., Ngadi, M. O., & Raghavan, G. S. V. (2009). Kinetics of mass transfer in microwave precooked and deep-fat fried chicken nuggets. *Journal of Food Engineering, 91*(1), 146–153.

AOAC. (1990). *Official methods of analysis*. Washington, DC: Association of Official Analytical Chemists.

Balasubramaniam, V. M., Chinnan, M. S., Mallikarjunan, P., & Phillips, R. D. (1997). The effect of edible film on oil uptake and moisture retention of a deep-fat fried poultry product. *Journal of Food Process Engineering, 20*(1), 17–29.

Balog, A., & Almeida Paz, I. C. L. (2007). Ostrich (*Struthio camellus*) carcass yield and meat quality parameters. *Brazilian Journal of Poultry Science, 9*, 215–220.

Budžaki, S., & Šeruga, B. (2005). Moisture loss and oil uptake during deep fat frying of "Kroštula" dough. *European Food Research and Technology, 220*(1), 90–95.

Cooper, R. G. (1999). Zimbabwean ostrich industry strategies into the 21st century. *Ostrich Farmer, 3*, 4–5.

Crank, J. (1975). *The arithmetics of diffusion* (2nd ed.). Oxford, UK: Oxford University Press.

Durán, M., Pedreschi, F., Moyano, P., & Troncoso, E. (2007). Oil partition in pre-treated potato slices during frying and cooling. *Journal of Food Engineering, 81*(1), 257–265.

Fernández-López, J., Jiménez, S., Sayas-Barberá, E., Sendra, E., & Pérez-Alvarez, J. A. (2006). Quality characteristics of ostrich (Struthio camelus) burgers. *Meat Science, 73*(2), 295–303.

Gamble, M. H., Rice, P., & Selman, J. D. (1987). Relationship between oil uptake and moisture loss during frying of potato slices from c.v. Record UK tubers. *International Journal of Food Science & Technology, 22*, 233–241.

Hallam, M. G. (1992). *The TOPAZ introduction to practical ostrich farming*. Harare: Superior Print and Packaging.

Hubbard, L. J., & Farkas, B. E. (2000). Influence of oil temperature on heat transfer during immersion frying. *Journal of Food Processing and Preservation, 24*, 143–162.

Jones, S. D. M., Robertson, W. M., & Brereton, D. (1995). *The ostrich as a meat animal*. Lacombe: Agriculture & Agri-Food Canada, Lacombe Research Centre.

Krokida, M. K., Oreopoulou, V., & Maroulis, Z. B. (2000). Water loss and oil uptake as a function of frying time. *Journal of Food Engineering, 44*(1), 39–46.

Lanza, M., Fasone, V., Galofaro, V., Barbagallo, D., Bella, M., & Pennisi, P. (2004). Citrus pulp as an ingredient in ostrich diet: Effects on meat quality. *Meat Science, 68*(2), 269–275.

Mai Tran, T. T., Chen, X. D., & Southern, C. (2007). Reducing oil content of fried potato crisps considerably using a 'sweet' pre-treatment technique. *Journal of Food Engineering, 80*(2), 719–726.

Mittal, G. S., & Zhang, J. (2000). Use of artificial neural network to predict temperature, moisture, and fat in slab-shaped foods with edible coatings during deep-fat frying. *Journal of Food Science, 65*, 978–983.

Moreira, R., Palau, J., & Sun, X. (1995). Simultaneous heat and mass transfer during deep fat frying of tortilla chips. *Journal of Food Process Engineering, 18*(3), 307–320.

Moreira, R. G., Sun, X., & Chen, Y. (1997). Factors affecting oil uptake in tortilla chips in deep-fat frying. *Journal of Food Engineering, 31*(4), 485–498.

Motarjemi, Y. (1989). *Determination of moisture diffusivity in foodstuffs*. Singapore: Singapore Institute of Food Science and Technology.

Ngadi, M., Dirani, K., & Oluka, S. (2006). Mass transfer characteristics of chicken nuggets. *International Journal of Food Engineering, 2*(3), 1–16.

Ngadi, M., Wang, Y., Adedeji, A. A., & Raghavan, G. S. V. (2009). Effect of microwave pretreatment on mass transfer during deep-fat frying of chicken nugget. *LWT-Food Science and Technology, 42*, 438–440.

Sahin, S., & Sumnu, S. G. (Eds.). (2009). *Advances in deep-fat frying of foods*. Boca Raton, FL: CRC Press.

Smith, W. A., Cilliers, S. C., Mellett, E. D., & Van Schalkwyk, S. J. (1995). *Ostrich production—a South African perspective*. Stellenbosch, South Africa: Department of Animal Sciences, University of Stellenbosch.

Sosa-Morales, M. E., Orzuna-Espíritu, R., & Vélez-Ruiz, J. F. (2006). Mass, thermal and quality aspects of deep-fat frying of pork meat. *Journal of Food Engineering, 77*(3), 731–738.

Vélez-Ruiz, J. F., Vergara-Balderas, F. T., Sosa-Morales, M. E., & Xique-Hernandez, J. (2002). Effect of temperature on the physical properties of chicken strips during deep-fat frying. *International Journal of Food Properties, 5*(1), 127–144.

William, R., & Mittal, G. S. (1999). Water transfer properties of polysaccharide film on fried pastry mix. *LWT-Food Science and Technology, 32*(7), 440–445.

Yildiz, M., & Dincer, I. (1995). Modelling the heat and mass transfer analysis during oil-frying of cylindrical sausages. *International Journal of Energy Research, 19*, 555–565.

Ziaiifar, A. M., Achir, N., Courtois, F., Trezzani, I., & Trystram, G. (2008). Review of mechanisms, conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying process. *International Journal of Food Science & Technology, 43*(8), 1410–1423.