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ORIGINAL PAPER

Effects of potato strip size and pre-drying method on french fries quality

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Abstract Potato strips of 8 mm × 8 mm and 10 mm × 10 mm after blanching were pre-dried using two methods: convective and vacuum-microwave (VM). A two-stage frying in rapeseed oil was applied to prepare French fries from pre-dried potato strips. The quality of French fries in terms of texture, oil content and color was analyzed based on the results from instrumental tests and sensory evaluation. Using vacuum-microwave instead of hot air resulted in substantial shortening of the potato strips' pre-drying time and decreasing the fat content in French fries. Pre-drying of potato strips, particularly by VM method, improved color and increased maximum cutting force as well as maximum cutting work estimated for French fries. French fries prepared from potato strips of 10 mm × 10 mm exhibited lower lightness, higher fat content and higher cutting strength compared with those made from potato strips of 8 mm × 8 mm. Based on the sensory results, it was found that the best French fries were those from pre-dried potato strips of 8 mm × 8 mm, independently of the pre-drying method used, and the worse were those from potato strips of 10 mm × 10 mm pre-dried with the convective method. SEM images confirmed structural changes occurred in potato tissue during pre-drying and frying.

Keywords Color · Convective drying · Oil content · Sensory evaluation · Texture · Vacuum microwave

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Introduction

One of the most popular fried products made of potato are French fries. In food processing, several kinds of French fries are distinguished according to their shape and length: long French fries (strips size 1 cm × 1 cm, 0.6 cm × 1 cm or 0.5 cm × 0.5 cm and length more than 7 cm), short French fries (strips of about 5 cm long), Paris French fries (small tubers of a diameter of about 30 mm, fried as a whole), cubes (rissole) and potato nuts [1]. Yet, regardless of their shape and length, French fries quality is assessed by the consumers on the basis of color, odor, taste, fat content and texture [2].

French fries color should be light, golden, without brown coloring penetrations or black spots or streaks. Color is determined by chemical composition of potato tubers (the amount of reducing sugars and/or starch), storing conditions, as well as by the parameters featuring the course of French fries production technological process [1]. Desired light golden color is obtained when frying in fat, as a result of Maillard reaction, and the time French fries need for gaining their color becomes shorter as subsequent frying cycles take place [1, 3].

Taste and smell of French fries are other important quality parameters; they should be specific of potato, fat in taste but without any flavor of bitterness, burning or rancid fat [1]. The taste inside French fries should be similar to that of freshly boiled potatoes. The external crispy part of French fries should not bear any flavor of oil or burnt sugar [2].

Consumers also pay close attention to fat content, with high contents limiting consumer acceptance. In completely fried French fries, fat amount should not exceed 7–10%, whereas in the ones partially fried before freezing, the maximum recommended limit is 4% [4]. Too much fat in a product is responsible for its oily flavor and at the same time makes production costs increase, whereas too low amount of fat deprives French fries of their natural taste and odor characteristic of any fried products [5, 6]. The kind of oil used for frying and some technological parameters, i.e. strip thickness, type of blanching, temperature, as well as time of pre-drying and frying and component ratio in dry potato matter, affect the amount of fat being absorbed by French fries. For instance, French fries fried in oil at temperatures below 150 °C absorb more fat and feature greasy texture [1, 2].

Texture is determined by structure, shape, chemical composition and other physical properties of a product [2, 7, 8], and it is an important quality parameter in French fries. The product should be characterized by appropriate texture, delicate and crispy skin, mealy inside, and when broken, the French fries surface should be even without any crack [9]. According to Burton [10] French fries' texture should not be greasy, and French fries should easily break when bent. The texture of fried potato products is affected, among other factors, by the dry matter and starch contents in potato tubers, components building cell walls, i.e. non-starch polysaccharides (NSP) and lignin (especially pectin compounds) [11], as well as by particular stages of French fries production technological process. Those processes include: blanching, pre-drying, initial frying and final frying [12].

Blanching is one of the most important stages of French fries production technological process, and it is often subjected to modifications [13]. The process of blanching consists of heat treatment applied to peeled and cube- or cubicoid-cut potatoes (in hot water of the temperature 60–85 °C or in steam). The blanching time depends on the potato variety used, the quality of the raw material and the size of potato strips. In food processing plants, blanching is sometimes applied in two- or three-stages at different water temperatures [1, 2].

In French fries producing plants, pre-drying is applied to improve the final product quality. The process of pre-drying potato strips results in the removal of extra-water from the potato strips surface. That surface water affects negatively on the fat being used for frying, which finally worsens French fries quality [12]. One of the most frequently used pre-drying system is the convective method, in which hot dry air supplies energy and removes the water; however, if not properly applied or applied for too long it can decrease the quality of potato strips. The main disadvantages of this method are low energy efficiency and long drying time in its final stage [14, 15].

Another system of pre-drying is the microwave method. Application of microwaves to remove water from the material has got many advantages. This method introduces heat inside the material (potato strips) and not only on the surface. Internal heating allows arbitrary modification of temperature inside potato strips and consequently reduces negative phenomena lowering product quality during the course of the pre-drying step [16]. Energy supply to the whole volume of the material results in considerable shortening of pre-drying time and, therefore, it shortens the time of contact between the dried materials with oxygen at elevated temperature. As a result diminishing of negative biochemical alteration effects does take place (e.g. fat oxidation) as well as maintaining appropriate color and nutritive value of dehydrated product [18]. Application of microwave heating at lowered pressure significantly increases drying efficiency and improves the quality of the product. However, it must be mentioned that microwave industrial application is difficult to control and standardize and could lead to a poor quality product caused by excessive heating [14] and non-homogenous temperature distribution [17, 18].

The high increase in consumption of French fries in Poland is leading to a decrease in the quality of the products being marketed. The introduction of a pre-drying step in the manufacturing of French fries can help in improving quality of the marketed products by lowering fat content and improving color and texture. Therefore, investigation regarding pre-drying methods is of considerable importance, as it will help in improving the final quality of Polish French fries. The present work was aimed at: (1) determination of the effects of potato strip size and pre-drying method on color, fat content and texture of French fries, and (2) studying drying kinetics in vacuum-microwave and convective potato strip drying.

Materials and methods

Materials

The raw material investigated was potato tubers, cultivar Santana, designed for French fries preparation, and purchased from a producer's factory near Wroclaw (Lower Silesia, Poland). The amount of potato tubers used for potato strips preparation was about 50 kg; only potato tubers of similar size and without any damages were selected for strips preparation.

Sample preparation

French fries were prepared by the two-stage frying method in rapeseed oil (Fig. 1). After washing and peeling (potato peeler Sirman model PP 4; Pieve di Curtarolo, Italy) the potato tubers were manually cut into rectangular strips 8 mm × 8 mm or 10 mm × 10 mm cross section and 60–70 mm long. Six hundred grams of potato strips were used for each treatment. The strips underwent one stage of blanching (for 10 min at 75 °C) using a Predom blanching machine (Zelmer, Poland). After blanching the potato strips were pre-dried by using vacuum-microwave or convective methods. Vacuum-microwave pre-drying was carried out using an SM-200 drier (Palzmatronika, Wrocław, Poland) under lowered pressure. Magnetrons power was set up at 480 W, and the pressure was changing in the range of 4–6 kPa. On the other hand, convective pre-drying was done using a drying equipment built in the Institute of Agricultural Engineering (Wrocław University of Environmental and Life Sciences, Wrocław, Poland). The convective pre-drying was performed at 75 °C with constant air speed of 4 m s^{-1}. After the pre-drying step, potato strips were pre-fried at 180 °C for 1 min using rapeseed oil in a ratio potato:oil of 1:20 and a Gastro fryer (Rm Gastro, S.R.O., model FE-04S, Czech Republic) and frozen at −25 °C in a Zanussi freezer (Zanussi, type ZCF 270; Nurenberg, Germany). Just before the quality tests, the frozen potato strips were deep fried using rapeseed oil again (180 °C). Times of the final deep frying step depended on the potato strips size and were 4 or 5 min for strips sections of 8 or 10 mm, respectively (Fig. 1). These frying times were decided based on sensory parameters; optimal temperatures and times of frying for potato strips of different size, which lead to proper texture of final French fries as previously described by Tajner-Czopek [19]. Control samples were blanched but not pre-dried.

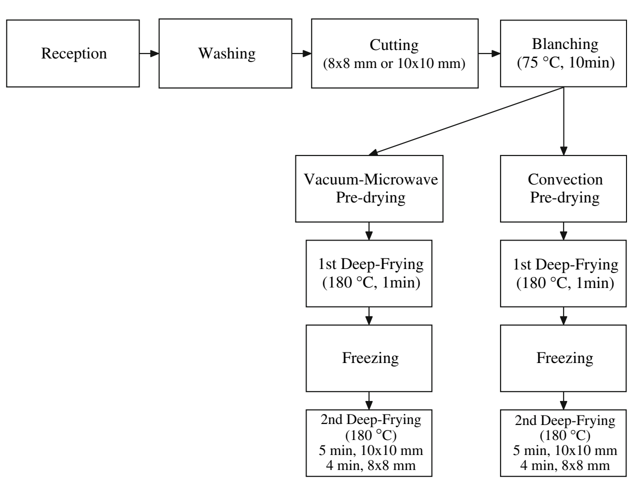

Fig. 1 Flow diagram showing preparation of French fries

Rapeseed is one of the most important oilseed crops in the world, and its oil has gained an excellent reputation for its nutritional qualities in the human diet [20]. Rapeseed is very popular in Poland and it is often used at Polish homes for deep-frying purposes. Moreover, Kita et al. [21] stated that potato crisps fried in rapeseed oil contained lower amounts of oil than the same product fried in other oils (sunflower, soybean, peanut, olive, and palm oils); similar conclusions were reached by Kita and Lisińska [22] when studying the texture of French fries.

Physico-chemical analyses

The dry matter of all potato strips (raw, blanched and pre-dried) and final French fries was measured by drying samples until constant weight at 105 °C [23]; the amount of water evaporated was measured gravimetrically.

The fat content was measured by the Soxhlet method which involved extraction of 2–3 g of French fries with diethyl ether for 2.5–3 h in a Büchi Distillation Unit B-316 [23].

Instrumental texture

Mechanical tests were carried out using an Instron 5544 strength testing machine (Instron, High Wycombe, UK) equipped with a 2KN load cell and a QTS-25 SB cutting attachment, moving at a speed of 250 mm min^{-1}. Instrumental texture tests were carried in 12 replications by cutting each French fries at their middle length (5 min after frying and at room temperature 20 ± 3 °C). The maximum cutting force (Ft_{max}) needed to cut each sample was determined from the diagram presenting the relationship between cutting force and sample deformation (Fig. 2) and the peak force expressed as N. The work necessary to obtain that force (work of cutting Wt_{max}) was also determined and was equivalent to the area under the shearing curve expressed as millijoules (Fig. 2). That area was limited by the point (A) of contact between the cutting attachment and the sample and the point (B) at which the cutting force reached its maximum value (Ft_{max}).

Instrumental color

The color of French fries was measured at room temperature, 20 ± 3 °C (5 min after frying), using a Minolta Chroma Meter CR-200 (Minolta Co. Ltd., Osaka, Japan). This spectrophotometer uses an illuminant D_{65} and a 10° observer as references, has an aperture diameter of 11 mm, and was calibrated using the CR-A43 calibration plate.

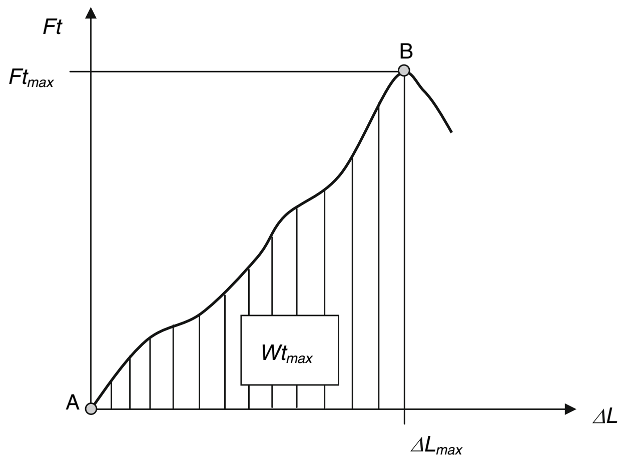

Fig. 2 Determination of maximum cutting force (Ft_{max}) and cutting work (Wt_{max})

Instrumental color data are provided as CIEL*a*b* coordinates, which define the color in a three-dimensional space. *L** is an approximate measurement of luminosity and ranges from 0 to 100; *a** takes positives values for reddish colors and negative values for the greenish ones, whereas *b** takes positive values for yellowish colors and negative values for the bluish ones [24–26].

Color analyses were run three times in eight different French fries (total of 24 measurements per value), and results were expressed as "mean ± standard error" [standard deviation/(number of samples)$^{1/2}$].

Sensory evaluation with trained panel

Sensory evaluation with trained panel was used to quantify the intensities of six organoleptic parameters defining the quality of French fries. A panel of five panelists, aged 20–50 years (three female and two male, all members of the Wrocław University of Environmental and Life Sciences), with sensory evaluation experience, was intensively trained in descriptive evaluation of French fries. The panel was formerly selected and trained following the ISO standard 8586-1 [27]. Panelists have evaluated French fries for the past 2 years almost in a weekly basis.

Measurements were performed in individual booths with controlled illumination and temperature [27, 28]. Individual samples of French fries were scored for intensity of six organoleptic attributes: (1) uniformity of blush (percentage of surface with the same color), (2) crispness (force and noise with which a food breaks or fractures when chewed with the molar teeth), (3) mealiness (internal textural attribute of fries characterized by combination of softness and juiciness), (4) oiliness (perception of oil amount contained in food), (5) taste (regular intensity of French fries taste), and (6) color (quality of food with respect to light reflected by it, e.g. golden color). At the beginning of the training exact definitions for these attributes were provided to panelists, and care was taken that all panelists understood the proper meaning of each attribute.

These attributes were scored using a structured scale of 1 to 5, where intermediate values could be marked by panelists (values were mathematically processed using only one decimal figure) and the following anchor points were defined:

- 1 = extremely low intensity,
- 2 = low intensity,
- 3 = regular intensity,
- 4 = high intensity, and
- 5 = extremely high intensity.

Six different samples were under study: control fries (blanched but not pre-dried) of 8 and 10 mm sections, convective pre-dried (10 or 15 min, respectively) fries of 8 and 10 mm sections, and VM pre-dried (6 min) fries of 8 and 10 mm sections. A complete block design was made, and the French fries were presented following a Williams Latin squared design balanced for order and first-order carryover effects [28]. The entire experiment was repeated three times (all panelists scored the six samples on each session for a total of three sessions), and the sensory scores were presented as the overall means ± standard error [standard deviation/(number of samples)$^{1/2}$].

Scanning electron microscopy

Changes in the structure of potato tissue were determined in potato strips before and after the pre-drying step and in French fries using a Leo-435VP (Zeiss Jena, Germany) scanning electron microscope (SEM). Samples for SEM were prepared following procedures previously described by Lisińska and Golubowska [29] and Lisińska et al. [30].

Statistical analysis

Statistical analyses (ANOVA and Tukey) were carried out using Statistica v.7.1 (Stat Soft Inc.). Homogeneous groups were determined with the multiplicative comparison test of Tukey (at significance level $\alpha = 0.05$). Standard deviations were estimated by means of Microsoft Excel 97. Table Curve 2D Windows v2.03 enabled mathematical modeling with the best determination coefficient.

Results and discussion

Dry matter

Figure 3 represents the changes in dry matter with time in potato strips during the pre-drying unit operation. The initial dry matter content of potato tubers was 20.8% and dry matter of potato strips after blanching was 20.3%. The kinetics of potato strips' pre-drying was described using linear and exponential functions for convective (C) and vacuum-microwave (VM) methods, respectively. Equations 1–4 show the goodness of the adjustments of experimental data to linear and exponential functions:

$$DM = 0.357 \cdot t + 20.50, \quad R^2 = 0.9977 \quad (C,\ 10\,\text{mm} \times 10\,\text{mm}) \tag{1}$$

$$DM = 0.477 \cdot t + 20.50, \quad R^2 = 0.9977 \quad (C,\ 8\,\text{mm} \times 8\,\text{mm}) \tag{2}$$

$$DM = 2.67 \cdot e^{\frac{t}{6.14}} + 17.74, \quad R^2 = 0.9975 \quad (\text{VM},\ 10\,\text{mm} \times 10\,\text{mm}) \tag{3}$$

$$DM = 5.18 \cdot e^{\frac{t}{9.04}} + 15.17 \quad R^2 = 0.9964 \quad (\text{VM},\ 8\,\text{mm} \times 8\,\text{mm}) \tag{4}$$

The drying rate curves showed in Fig. 4 are derivatives of the drying kinetic curves shown in Fig. 3. The shape of the functions found indicated that a constant drying rate should be expected when pre-drying potato strips by the convective method, whereas with the microwave heating an increase in the pre-drying rate with time was found (Fig. 4). As reported by Jones [31] during microwave drying the material warms up in bulk, which increases the rate of water evaporation; whereas major disadvantages in the hot air drying of foods are low energy efficiency and lengthy drying time in the falling rate period [32]. Lisińska and Gołubowska [29] reported that the optimal dry matter content in potato strips after the pre-drying process should be around 25%. Based on the results presented here, it can be stated that pre-drying of potato strips by convective method at the temperature of 75 °C can yield such dry matter content after 10 and 15 min for strips of cross-section sizes of 8 and 10 mm, respectively. On the other hand, pre-drying with the vacuum microwave method only needed 6 min, independently of strip size.

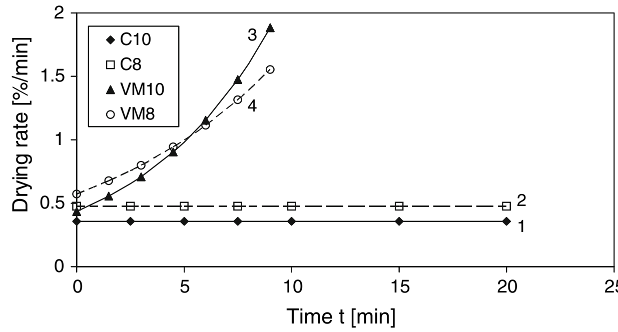

Fig. 4 Drying rate curves of potato strips pre-dried by the convective method (*C*): *1* (10 mm × 10 mm), *2* (8 mm × 8 mm), and vacuum microwave method (*VM*): *3* (10 mm × 10 mm) and *4* (8 mm× 8 mm)

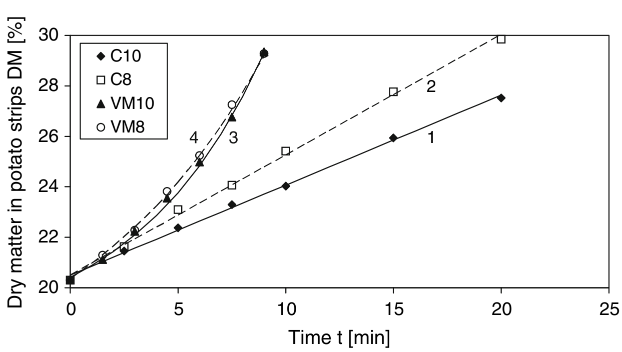

Fig. 3 Kinetics of potato strips pre-dried by the convective method (*C*): *1* (10 mm × 10 mm), *2* (8 mm × 8 mm), and vacuum-microwave method (*VM*): *3* (10 mm × 10 mm) and *4* (8 mm × 8 mm)

Fat uptake

Pre-drying of potatoes before frying using microwave, hot-air treatment or baking has previously resulted in a significant reduction in oil content of French fries in several studies [5, 33–36]. However, this statement produces controversy among authors. For instance, Du Pont et al. [37] claim that there is no relationship between moisture content and fat uptake. In a similar way, Moreira et al. [38] showed that higher water content in tortilla chips resulted in higher final oil content. On the other hand, Alvarez et al. [39] explained that sustaining high moisture content in the final product results in a low final fat content, because the internal volume of the strips that could be occupied by oil during frying is less.

What it is clear is that too much fat content in a fried product endows it with an oily taste, whereas too little fat content deprives it of the typical taste and odor of the fried product. It is assumed that French fries after the first stage of frying should contain up to 4% fat, whereas the finished product showed have up to 7% [2].

The fat content in fries was connected with the size of potato strips and pre-drying method of the strips after the blanching step (Fig. 5).

It was found that the fat content in French fries of 10 mm × 10 mm size was higher than that in French fries of 8 mm × 8 mm size. Gamble and Rice [35] stated that fat uptake during frying depended positively on the ratio surface/volume of the foods. Based on this statement, it was

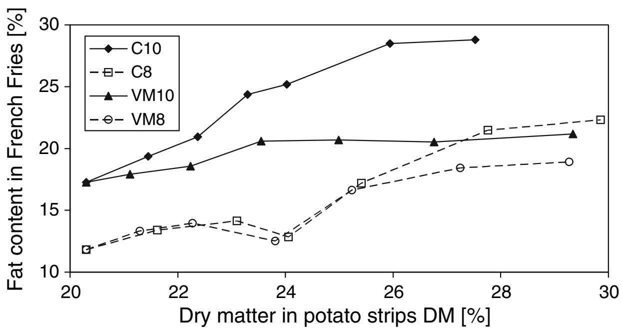

Fig. 5 Fat content in French fries as dependent on the pre-drying methods (*C* convective, *VM* vacuum-microwave, *Control* sample after blanching and without pre-drying) and potato strip size (8 mm × 8 mm or 10 mm × 10 mm)

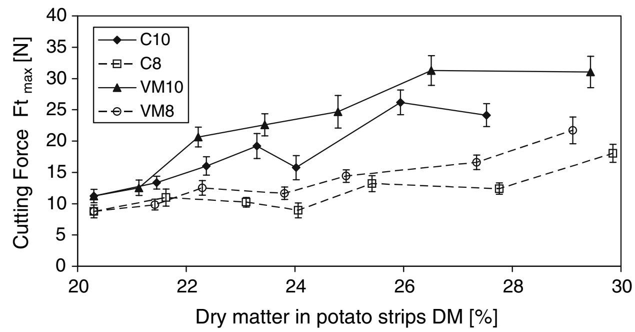

Fig. 6 Maximum cutting force (Ft_{max}) of French fries as dependent on the pre-drying methods (*C* convective, *VM* vacuum-microwave, *Control* sample after blanching and without pre-drying) and potato strip size (8 mm × 8 mm or 10 mm × 10 mm)

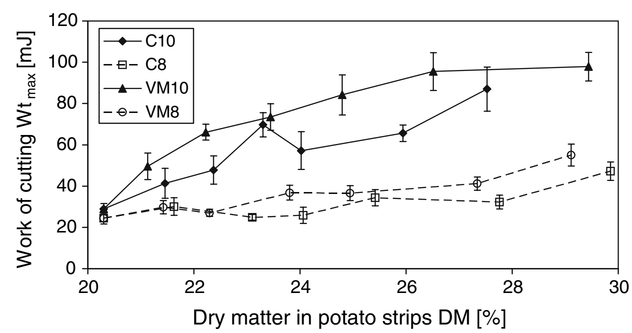

Fig. 7 Maximum cutting work of French fries as dependent on the pre-drying method and the size of potato strips

expected that French fries with 8 mm section should contain more fat than 10 mm-fries due to its 1.25 higher surface/volume ratio. However, this was not experimentally found. This was possible due to the fact that 10 mm-French fries were fried for 5 min, whereas 8 mm-fries were fried for less time, only 4 min. This difference in time was needed to obtain an equivalent texture of final products, as previously mentioned. Gamble et al. [40] positively correlated oil content of potato slices with the square root of frying time.

Fries prepared from strips pre-dried with the VM method absorbed less fat than fries pre-dried with the convective method. In convective pre-drying, the distribution of water is not uniform; the cells in the outer surface contain less water than those in the inner part of the potato strips due to external heating caused by hot air. On the other hand, in VM pre-drying, the distribution of water is uniform in the whole potato strip. Assuming that oil absorption is mainly a surface phenomenon involving equilibrium between adhesion and drainage of oil during the cooling step [41], it can be explained that VM caused less oil content in French fries than convective pre-drying.

Instrumental texture

The maximum cutting force needed to cut the French fries increased steadily with increasing dry matter contents of the strips (Fig. 6) and the cutting work increased in a similar way (Fig. 7). Tajner-Czopek and Figiel [42] in an earlier study made on French fries stated that cutting work was correlated with the maximum cutting force. The hardness of the French fries increased as the dry matter of the potato strips increased. It can be stated that the cutting force and cutting work were higher for French fries of 10 mm × 10 mm than those of 8 mm × 8 mm. Besides, it was found that both cutting force and cutting work were lower for strips pre-dried by the convective method (the samples analyzed exhibited softer consistency) than those pre-dried by the vacuum-microwave method.

Instrumental color

Table 1 summarized the effects of different pre-drying methods and the size of potato strips on CIEL*a*b* color coordinates of French fries. The values of luminosity, L^*, ranged from 41.93 (control, 10 mm × 10 mm) up to 52.95 (VM, 8 mm × 8 mm); those of green-red coordinate, a^*, ranged from 3.20 (C, 8 mm × 8 mm) up to 13.64 (control, 10 mm × 10 mm); whereas those of the blue-yellow coordinate, b^*, ranged from 23.37 (control, 8 mm × 8 mm) up to 26.37 (C and VM, 8 mm × 8 mm). The statistical study of experimental data showed that differences in color of French fries were mainly due to the strip size rather than the pre-drying method.

Better color characteristics (lighter and more greenish and yellowish samples) were found in French fries prepared from 8 mm × 8 mm potato strips.

Pre-drying potato strips by C or VM methods led to French fries with higher intensities of green (lower values of a^*) and yellow (higher values of b^*) colors and higher values of lightness compared to non-pre-dried French fries. However, no significant differences could be established among C-pre-dried and VM-pre-dried French fries.

Feng and Tang [43] found that pre-drying with hot air was more aggressive than vacuum-microwave on the color

Table 1 French fries color coordinates as dependent on the pre-drying methods

Treatment	Instrumental color		
	L^*	a^*	b^*
Control (8 mm × 8 mm)	46.19 ± 2.25†	4.84 ± 0.82	23.37 ± 1.63
Control (10 mm × 10 mm)	41.93 ± 1.88	13.64 ± 0.73	23.54 ± 2.09
C (8 mm × 8 mm)	51.33 ± 1.09	4.09 ± 1.13	26.14 ± 0.69
C (10 mm × 10 mm)	42.16 ± 0.95	8.78 ± 0.79	25.96 ± 1.24
VM (8 mm × 8 mm)	51.55 ± 1.60	4.73 ± 1.33	26.65 ± 0.81
VM (10 mm × 10 mm)	43.65 ± 1.33	7.97 ± 0.26	26.01 ± 1.38
ANOVA test			
Variation source			
Strip size	***‡	***	NS
Pre-drying method	***	***	*
Tukey's multiple range test			
Strip size			
8 mm × 8 mm	49.69 a¥	4.55 b	25.39
10 mm × 10 mm	42.58 b	17.60 a	25.17
Pre-drying method			
Control	44.06 b	9.24 a	23.46 b
Convective, *C*	46.75 a	6.44 b	26.05 a
Vacuum-microwave, VM	47.60 a	6.35 b	26.32 a

C convective, *VM* vacuum-microwave, *Control* sample after blanching and without pre-drying and potato strip size (8 mm × 8 mm or 10 mm × 10 mm)

† Values are given as mean ± standard error

‡ *NS* not significant *F* ratio ($p < 0.05$); *, **, and ***, significant at $p < 0.05$, 0.01, and 0.001, respectively

¥ Values followed by the same letter, within the same variation source, were not significantly different ($p < 0.05$), Tukey's multiple-range test

Table 2 Intensity of sensory attributes of French fries as dependent on the pre-drying methods

Treatment	Sensory intensity					
	Blush	Crispiness	Mealiness	Oiliness	Taste	Color
Control (8 mm × 8 mm)	3.8 ± 0.2†	3.0 ± 0.1	3.0 ± 0.1	2.8 ± 0.2	3.8 ± 0.2	4.0 ± 0.1
Control (10 mm × 10 mm)	3.8 ± 0.1	3.0 ± 0.1	3.0 ± 0.1	3.0 ± 0.1	3.8 ± 0.2	4.0 ± 0.1
C (8 mm × 8 mm)	4.0 ± 0.1	3.4 ± 0.2	3.6 ± 0.3	3.6 ± 0.2	4.1 ± 0.2	4.0 ± 0.3
C (10 mm × 10 mm)	3.2 ± 0.4	3.6 ± 0.2	3.3 ± 0.2	3.0 ± 0.3	3.7 ± 0.2	3.0 ± 0.3
VM (8 mm × 8 mm)	3.9 ± 0.1	3.6 ± 0.2	3.8 ± 0.1	3.7 ± 0.2	4.2 ± 0.2	4.5 ± 0.2
VM (10 mm × 10 mm)	3.4 ± 0.3	3.5 ± 0.3	3.3 ± 0.2	3.4 ± 0.2	3.5 ± 0.2	3.4 ± 0.2
ANOVA test						
Variation source						
Strip size	NS‡	NS	**	NS	***	***
Pre-drying method	NS	NS	***	*	NS	NS
Tukey's multiple range test						
Strip size						
8 mm × 8 mm	3.9	3.4	3.5 a¥	3.4	4.0 a	4.2 a
10 mm × 10 mm	3.5	3.3	3.2 b	3.1	3.7 b	3.5 b
Pre-drying method						
Control	3.8	3.0	3.0 b	2.9 b	3.8	4.0
Convective, *C*	3.6	3.5	3.5 a	3.3 a	3.9	3.5
Vacuum-microwave, VM	3.6	3.6	3.6 a	3.6 a	3.9	4.0

C convective, *VM* vacuum-microwave, *Control* sample after blanching and without pre-drying) and potato strip size (8 mm × 8 mm or 10 mm × 10 mm)

† Data are the mean of 15 values (5 panelists × 3 replicates) ± standard error.

‡ *NS* not significant *F* ratio ($p < 0.05$); *, **, and ***, significant at $p < 0.05$, 0.01, and 0.001, respectively

¥ Values followed by the same letter, within the same variation source, were not significantly different ($p < 0.05$), Tukey's multiple-range test

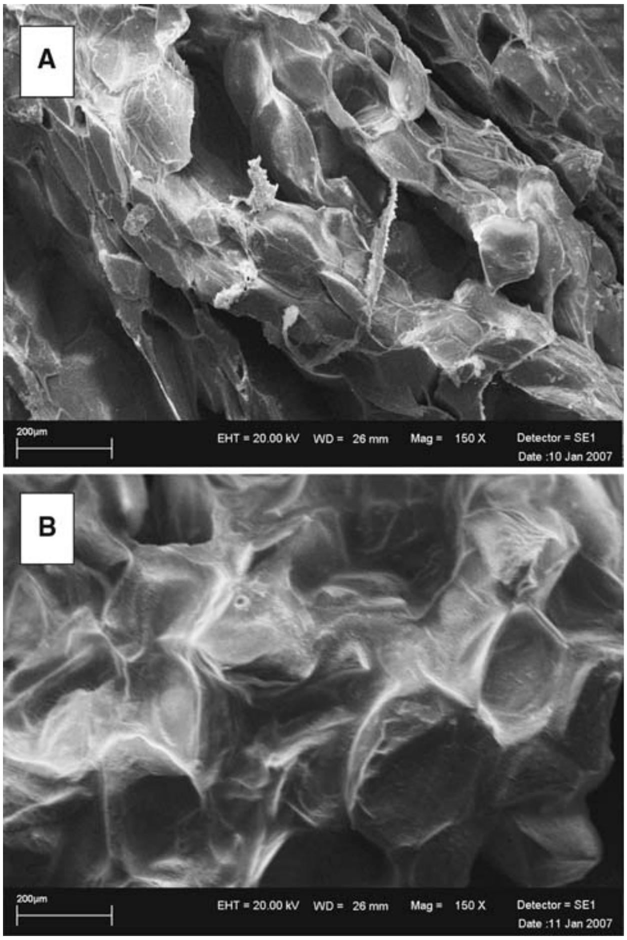

Fig. 8 Cross-sections of potato strips pre-dried by convective (**a**) and vacuum-microwave (**b**) methods

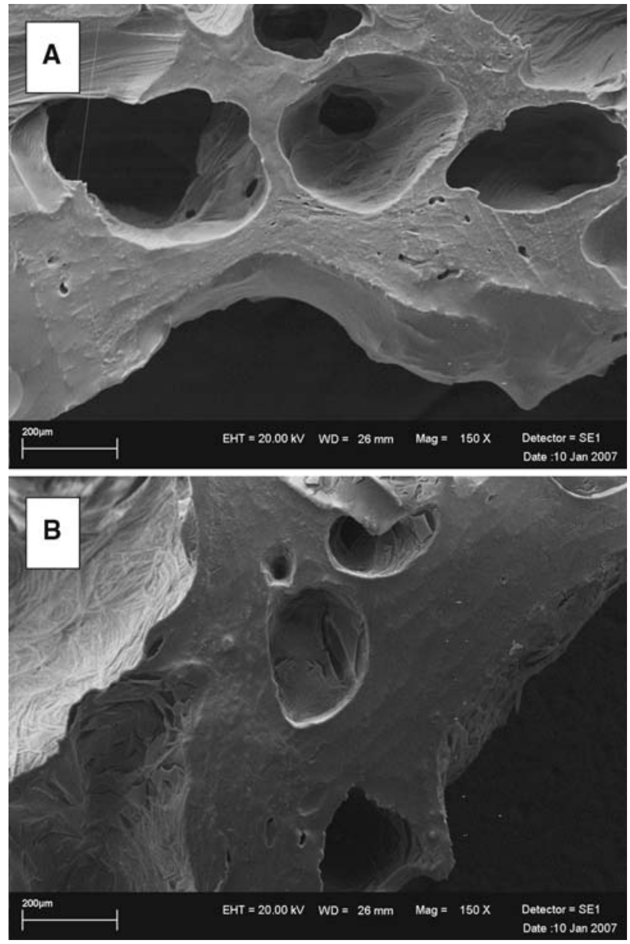

Fig. 9 Cross-sections of French fries obtained from potato strips pre-dried by convective (**a**) and vacuum-microwave (**b**) methods

of sliced apples, providing darker samples. Maskan [32] reported similar results for the color of fresh bananas. This author reported that the drying time played an essential role in color formation, with color of bananas becoming darker for higher temperatures and longer drying times. Fruits and vegetables are well suited for drying with the vacuum-microwave method because of their large water content, which can efficiently absorb the microwave power. However, the time of drying should be short if high quality dried products are required, for instance in potatoes [44] and bananas [14, 15].

Sensory evaluation

Sensory analyses of food color, taste, odor and texture are used in maintenance and control of food quality throughout the manufacturing process and in the final product [45]. Sensory evaluation of the French fries made from potato strips of 8 mm × 8 mm or 10 mm × 10 mm after convective or vacuum-microwave pre-drying was carried out to obtain preliminary information on their quality (Table 2).

The pre-drying step, independently of the applied method, significantly increased the values of the intensities of taste, color and texture (crispiness) of the French fries made from 8 mm × 8 mm potato strips. On the contrary, the convective pre-drying on 10 mm × 10 mm French fries' sensory attributes significantly decreased the intensities of some of the studied sensory attributes (taste, color, etc.); however, the quality of the French fries was not so drastically reduced when the vacuum-microwave method was applied. The high temperatures and long drying times, required to remove the water from the sugar containing raw material in conventional drying, may cause serious damage to the flavor, color, nutritional value, reduction in bulk density and rehydration capacity of the dried product [15]. On the other hand, Drouzas and Schubert [14] found that vacuum-microwave drying can result in poor quality products if not properly applied, and suggested that due to high cost of energy the method should be used only in cases where high quality of final product is demanded.

Scanning electron microscopy images

Figure 8 shows cross-sections of potato strips pre-dried by convective (A) and VM (B) methods, respectively. The structure of potato strips pre-dried in convection was not regular; deformed cells are responsible for shrinkage, which is typical for convective dehydration. On the other hand, the structure of potato strips pre-dried in VM was more regular, and the cells shrunk with less intensity. In VM dehydration, microwaves penetrate to the interior of the material causing water to boil at relatively low temperature, which depends on the level of vacuum pressure in the drying chamber. This creates a large vapor pressure in the center of the material, allowing rapid transport of moisture out of the product and preventing structural collapse. This process, referred to as the puffing phenomenon, creates a porous texture of the product [46]. However, as it was previously stated, French fries obtained from potato strips pre-dried using VM method exhibited lower fat content (Fig. 5) and harder texture (Fig. 6) compared with those obtained from potato strips pre-dried by convection. During frying the convective pre-dried shrank cells, especially those at the strips surface, were absorbing fat and becoming more regular (Fig. 9a) than VM pre-dried puffed cells, which under the high temperature underwent breakage and created less regular spaces (Fig. 9b). This explanation needs more consideration and has to be supported by an extended study on the effect of potato strips pre-drying using both methods on the process of water and fat migration at high temperature, changing French fries structure during frying.

Conclusions

The kinetics of pre-drying the potato strips could be described by a linear function in the convective method and by an exponential function in the vacuum microwave method. The pre-drying time needed to obtain an optimal dry mass content (ca. 25%) in the vacuum microwave method (6 min) was significantly shorter than that in the convective method (10 and 15 min for 8 mm × 8 mm and 10 mm × 10 mm strips, respectively). French fries made of strips pre-dried by the vacuum microwave method absorbed less fat than those pre-dried by the convective method. Besides, the fat content in 10 mm × 10 mm French fries was higher than in the 8 mm × 8 mm ones because of longer frying time required by the technological process. Pre-drying of potato strips, particularly by vacuum microwave method, improved color and increased maximum cutting force as well as maximum cutting work estimated for French fries. French fries prepared from potato strips of 10 mm × 10 mm exhibited lower lightness and higher cutting strength comparing with those made from potato strips of 8 mm × 8 mm. Based on the sensory results, it was found that the best French fries were made from pre-dried potato strips of 8 mm × 8 mm, independently of the pre-drying method used, and the worse were made from potato strips of 10 mm × 10 mm pre-dried with the convective method. Therefore, our final recommendation is that pre-drying is absolutely necessary to obtain the best possible French fries and using vacuum-microwave at this operation unit will help in reducing the oiliness and in improving color and texture.

References

1. Talburt WF, Smith O (1987) Potato processing, 4th edn. Avi van Nostrand Reinhold Company, New York
2. Lisińska G, Leszczyński W (1989) Potato science and technology. Elsevier, London
3. Agblor A, Scanlon MG (2000) Potato Res 43:163–178
4. Lisińska G (1994) Postępy Nauk Rolniczych 1:32–40
5. Krokida MK, Oreopoulu V, Maroulis ZB, Marinos-Kouris D (2001a) J Food Eng 49(4):347–354
6. Krokida MK, Oreopoulou V, Maroulis ZB, Marinos-Kouris D (2001b) Drying Technol 19:879–935
7. Bourne MC (2002) Food texture and viscosity. Concept and measurement, 2nd edn. Academic, London
8. Szczesniak-Surmacka A (2002) Food Qual Prefer 13:215–225
9. Jaswal AS (1991) Am Potato J 68:835–841
10. Bourton WG (1989) The potato, 3rd edn. Longman, Wiley, New York
11. Tajner-Czopek A (2003) Nahrung/Food 47228-231
12. Agblor A, Scanlon MG (1998) Am J Potato Res 75:245–255
13. Abu-Ghannam N, Crowley H (2006) J Food Eng 74:335–344
14. Drouzas AE, Schubert H (1996) J Food Eng 28:203–209
15. Drouzas AE, Tsami E, Saravacos GD (1999) J Food Eng 39:117–122
16. Szarycz M, Kramkowski R, Kamiński E (2002) Inz Rolnicza 2:47–63
17. Datta AK (1990) Chem Eng Prog 86(6):47–53
18. Kelen A, Pallai-Varsanyi E, Ress S, Nagy T, Pintye-Hodi K (2006) Eur J Pharm Biopharm 62:101–109
19. Tajner-Czopek A (2003) Nahrung/Food 47(4):228–231
20. Przybylski R (2007) http://www.canola-council.org
21. Kita A, Lisińska G, Gołubowska G (2007) Food Chem 102:1–5
22. Kita A, Lisińska G (2005) J Sci Food Agric 85:2600–2604
23. AOAC (1995) Official methods of analysis of AOAC International, 16th edn. AOAC International, Gaithersburg
24. Minolta (1994) Precise color communication. Color control from feeling to instrumentation. Minolta, Osaka
25. Pomeranz Y, Meloan CE (1994) Food analysis. Theory and practice, 3rd edn. Chapman & Hall, New York
26. Pérez-López A, Beltran F, Serrano-Megías M, Saura López D, Carbonell-Barrachina AA (2006) Eur Food Res Technol 222:516–520
27. AENOR (Asociación Española de Normalización y Certificación) (1997) Sensory evaluation of food. UNE standards [In Spanish]. AENOR, Madrid, Spain
28. Meilgaard M, Civille GV, Carr BT (1999) Selection and training of panel members. In: Sensory evaluation techniques, 3rd edn. CRC, Boca Raton, pp 133–159
29. Lisińska G, Gołubowska G (2005) Food Chem 93:681–687

30. Lisińska G, Tajner-Czopek A, Kalum L (2007) Food Chem 102:1055–1060
31. Jones PL (1992) Electromagnetic wave energy in drying processes. In: Drying'92. Part A. Elsevier, Amsterdam, pp 114–136
32. Maskan M (2000) J Food Eng 44:71–78
33. Lamberg I, Hallostrom B, Olsson H (1990) Lebenson Wiss Technol 23:295–300
34. Moyano PC, Rioseco VK, Gonzales PA (2002) J Food Eng 54:249–255
35. Gamble MH, Rice P (1988) Int J Food Sci Technol 22:535–539
36. Pedreschi F, Moyano P (2005) Lebenson Wiss Technol 37:679–685
37. Du Pont MS, Kirby AR, Smith AC (1992) Int J Food Sci Technol 27:285–295
38. Moreira RG, Sun X, Chen Y (1997) J Food Eng 31:485–498
39. Alvarez MD, Morillo MJ, Canet W (2000) Eur Food Res Technol 211:326–335
40. Gamble MH, Rice P, Selman JD (1987) Int J Food Sci Technol 22:233–241
41. Ufheil G, Esher F (1996) Lebenson Wiss Technol 29:640–644
42. Tajner-Czopek A, Figiel A (2003) Pol J Food Nutr Sci 12(53):136–140
43. Feng T, Tang J (1998) J Food Sci 63:679–683
44. Bouraoui M, Richard P, Durance T (1994) J Food Proc Eng 17:353–359
45. Maskan M (2001) J Food Eng 48:169–175
46. Sham PWY, Scaman CH, Durance TD (2001) J Food Sci 66(9):1341–1347