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Analysis of dehydration kinetics, status of water and oil distribution of microwave-assisted vacuum frying potato chips combined with NMR and confocal laser scanning microscopy

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ABSTRACT

In this study, the dehydration kinetics, status of water and oil distribution of microwave-assisted vacuum frying (MVF) potato chips were analyzed combining with NMR and confocal laser scanning microscopy (CLSM). Results showed that the MVF markedly increased the moisture evaporation kinetics and effective moisture diffusivity compared to vacuum frying (VF). The higher microwave power level (1000 W) used achieved higher moisture evaporation rate and higher effective moisture diffusivity, The Logarithmic model exhibited the best fit for the obtained data of MR versus frying time in the MVF. The NMR analysis showed the free water in the samples firstly evaporate and the linkage between water and structure of materials becomes tighter with the frying time. The total oil content, surface and structural oil content were all significantly lower in MVF samples than that in VF samples. The CLSM analysis confirmed that less oil adhere to the surface and less oil trapped in the structure in MVF slices. The surface morphology showed that there were less ruptured and damaged cells in MVF samples and helped to explain the reduction of oil content.

1. Introduction

Vacuum frying (VF) is used to fry fruits and vegetables under sub-atmospheric pressure, preferably below 50 Torr (6.65 kPa). It lowers the boiling point of frying oil and moisture in food and produces better quality fried foods with less oil content compared with atmospheric frying (Albertos et al., 2016; Andrés-Bello, García-Segovia, & Martínez-Monzó, 2011). With the increasing of the demands for economy and efficiency and the consumer preference for low-fat or fat-free products, researches have been concentrated on approaches to improve the efficiency of processing and reduce oil absorption of the product (Moreira, Da Silva, & Gomes, 2009; Tarmizi & Niranjan, 2010), and many food industries also have been driven to produce lower oil content fried products as well as desirable texture and flavor.

In recent years, attempts have been made by applying microwave in the frying process to improve the efficiency of the frying process and the quality of the fried products. The application of microwave in freeze drying had been reported by Jiang, Zhang, Liu, Mujumdar, and Liu (2013) with saving up to 35.7% energy and 40% of drying time. The use of microwave in vacuum drying had been described by Bai-Ngew, Therdthai, and Dhamvithee (2011) with a clear increase in the drying rate, and reduced the fat content by at least 90% compared with conventionally deep fried durian chips. The application of microwave in the process of vacuum frying has been conducted to have a lower oil content in the fruits and vegetables and more efficiency and desirable texture than vacuum frying (Gharachorloo, Ghavami, Mahdiani, & Azizinezhad, 2009; Oztop, Sahin, & Sumnu, 2007; Sensoy, Sahin, & Sumnu, 2012). Microwave-assisted vacuum frying (MVF) is a special vacuum frying process in which the microwave is used as the unique heating resource (Su, Zhang, Zhang, Adhikari, & Yang, 2016). MVF has been reported to be an efficient method with faster dehydration and shown to produce fried fruits and vegetables with lower oil content, more desirable texture and flavor characteristics when compared with VF (Quan, Zhang, Zhang, & Adhikari, 2014; Su, Zhang, & Zhang, 2015).

Water loss and oil uptake are two main mass transport phenomena

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Abbreviations: MVF, microwave-assisted vacuum frying; VF, vacuum frying; NMR, nuclear magnetic resonance; CLSM, confocal laser scanning microscopy; MR, moisture ratio; D_{eff}, effective moisture diffusivity (m^2/s); FW, free water; BW, bound water; IW, immobilized water; TOC, total oil content; SUOC, surface oil content; STOC, structural oil content

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during frying (Adedeji, Ngadi, & Raghavan, 2009; Dehghan Nasiri, Mohebbi, Tabatabaee Yazdi, & Haddad Khodaparast, 2011). The development of microstructural changes and oily dry surface is a major structural transformation occurred during the frying of potato chips (Baumann & Escher, 1995; F. Pedreschi, Aguilera, & Pyle, 2001). Bouchon and Aguilera (2001) suggested that oil uptake is mainly a surface phenomenon and the final oil content is depending on the equilibrium between draining and porous oil suction. Bouchon, Aguilera, and Pyle (2003) also observed that oil uptake and water removal are not synchronous phenomena in deep-fat frying. After cooling, oil was located either on the surface of the chip or suctioned into the porous crust microstructure, with an inverse relationship between them for increasing frying times. It was later confirmed by Pedreschi, Cocio, Moyano, and Troncoso (2008) and Zhang, Li, Ding, and Fan (2015). Durán, Pedreschi, Moyano, and Troncoso (2007) found the oil could penetrate in chip microstructure either during frying or during cooling when the oil wetting the potato chip surface at the end of the frying process, penetrates into the chip microstructure by vacuum forces created by evaporative cooling. Dueik, Moreno, and Bouchon (2012) observed the oil distribution of different vegetable tissues after vacuum frying and found a linear relationship between porosity and final oil content in vacuum and atmospheric fried chips. The microstructural changes and the form of porous structure during the frying process were probably the result of water migration as suggested by Aguilera, Cadoche, pez, and Gutierrez (2001). It can be conducted that the manner and rate of moisture evaporation which made the microstructural changes play an important role in the oil absorption and oil location in fried products.

In this research, the dehydration kinetics, status of water and oil distribution in microwave-assisted vacuum frying (MVF) potato chips were investigated combining with NMR and CLSM. Experiments were conducted using MVF with different microwave power levels and the vacuum frying for reference. The drying kinetics of MVF was measured using the variation of moisture content and effective moisture diffusivity compared to VF. The best fit dehydration model was detected for the MVF drying process and the water removing process in MVF was also analyzed by NMR. The oil uptake containing surface oil content, the structural oil content and total oil content during the MVF was analyzed respectively contrast with VF. Some important microstructural aspects such as oil location, cell walls and surface morphology were observed by CLSM to interpret the mechanism of lower oil content in the MVF potato chips with the VF samples as reference.

2. Materials and methods

2.1. Materials

Fresh potato (*Solanum tuberosum* L.) and palm oil (by Yihai Kerry Company, Shanghai, China; 24°) were purchased from a local market in Wuxi, China. Fresh potatoes were washed, peeled and sliced (2 ± 0.2 mm thick and 36 ± 1 mm diameter) with a circular cutting mold. Potato slices were blanched at 92 °C for 3 min with the ratio of potato to water 1:8 (w/w), cooled under running tap water for 1 min. The surface of the slices was wiped dry using an absorbent paper.

2.2. Frying methods

2.2.1. Microwave-assisted vacuum frying

The microwave-assisted vacuum frying experiments were carried out in the MVF instrument described earlier by Su et al. (2015). The experiments were carried out at the power of 600 W, 800 W and 1000 W, respectively to determine the drying kinetics of MVF. After the oil (5 L) being heated to the target temperature (100 ± 2 °C), identical batch of 50 g potato chips was fried at the vacuum degree of 15 ± 2 kPa for various time intervals at the temperature of 100 °C until the samples reached the ending point (moisture content ≤ 4 g water/100 g total). After frying, the chips were centrifuged in the vessel with the relative centrifugal force of 10.02 (× g) for 5 min to remove excess oil under the vacuum pressure (15 kPa). Each condition was repeated in triplicate at different dates. After frying, samples produced by each frying condition were sealed in a plastic bag and all the relevant test parameters (moisture content and oil content) were taken within 15 min.

2.2.2. Vacuum frying

The vacuum frying experiments were carried out in a vacuum fryer as described by Chen, Zhang, and Fang (2014) and Su et al. (2016). The heating power of the VF instrument is 4000 W. Same batch of 50 g potato chips was fried in 5 L of palm oil at the same temperature (100 ± 2 °C) and vacuum degree (15 ± 2 Pa) for various time intervals until the samples reached the ending point (moisture content ≤ 4 g water/100 g total) as a reference. After frying, the chips were also centrifuged with the relative centrifugal force of 10.02 (× g) as was done in the case of MVF under vacuum pressure (15 kPa). After frying, samples produced by each frying condition were sealed in a plastic bag and same experimental data were taken as the MVF within 15 min. Each frying condition was repeated in triplicate at different dates.

2.3. Analysis methods

2.3.1. Drying kinetics of MVF

The residual moisture content of the samples was determined by using an oven method (AOAC, 1995). The moisture content in the sample during frying was expressed as g/100 g product wet basis. The moisture ratio (MR) in the sample is calculated from the moisture content using Eq. (1) as below:

$$MR = \frac{Mt - Me}{M0 - Me} \tag{1}$$

where M_t is the moisture content (kg water/kg defatted dry matter) of samples at any time and M_e is the equilibrium moisture content during the frying process; M_0 is the initial moisture content of the samples. It was considered that M_e is zero ($M_e = 0$) in the present frying process, because the value of M_e is negligible compared to M_t or M_0 (Mehmet. Başlar, Kılıçlı, & Yalinkilic, 2015). Then, the moisture ratio can be simplified as MR = M_t/M_0.

The effective moisture diffusivity (D_{eff}) was calculated according to Eq. (2) for potato samples during the frying:

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}\, t}{4L^2}\right) \tag{2}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), L is the half thickness of potato slice (m) and t is the drying time (s).

Moreover, the obtained drying data of the value of MR versus time during MVF in this work was also modeled by 10 different empirical models and the equations of them are presented in Table 1.

2.3.2. Determination of moisture distribution by NMR

A low-field pulsed NMR Analyzer (PQ001, Shanghai Niumag Corporation, China) with a frequency field of 22.0 MHz was used in the experiment. The instrument was equipped with a radiofrequency coil of 30 mm and the operation temperature of the probe was held at 32 °C. The magnetic field intensity of this equipment is 0.5 ± 0.08 T. Sample was placed in a 10-mm glass tube and inserted in the nuclear magnetic resonance (NMR) probe. Carr–Purcell–Meiboom–Gill (CPMG) pulse sequence was employed to measure spin–spin relaxation time, T_2. Typical pulse parameters were as follows: dwell time 0.04 ms, echo time 0.80 ms, recycle time 1500 ms, echo count 4000, and scan repetitions 32. The proportion was calculated at per gram. Each measurement was performed in triplicate. T_2 distribution curves were constructed based on logarithmic coordinates of the original data.