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Enhancement of water removing and the quality of fried purple-fleshed sweet potato in the vacuum frying by combined power ultrasound and microwave technology

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ABSTRACT

The combination of ultrasound and microwave in vacuum frying system was investigated to achieve higher drying efficiency and quality attributes of fried products. Purple-fleshed potato were used as test specimen and different power levels of microwave (0 W, 600 W, 800 W) and ultrasound (0 W, 300 W, 600 W) during vacuum frying. Drying kinetics, dielectric properties, moisture state variation and quality attributes of fried samples were measured in a vacuum frying (VF), and an innovatively designed ultrasound and microwave assisted vacuum frying (USMVF) equipment. The USMVF process markedly increased the moisture evaporation rate and effective moisture diffusivity compared to VF process. The oil uptake was reduced by about 16–34%, the water activity and the shrinkage was lowered, the texture (crispness) and the color of fried samples were greatly improved. The higher ultrasound and microwave power level in USMVF made a greater improvement. The total anthocyanin levels and retention of fried purple-fleshed potato chips was the highest (123.52 mg/100 g solids and 79.51% retention, respectively) among all treatments in US600M800VF process. The SEM analysis revealed a more porous and disruption microstructure in USMVF sample.

1. Introduction

The purple-fleshed sweet potato (*Ipomoea batatas*) has received increasing attention from researchers in recent years due to its special flavor and high levels of nutritional value [1,2]. Frying is an alternative processing method to increase the consumption with desired taste properties. Vacuum frying (VF) is a feasible option to fry fruits and vegetables under sub-atmospheric pressure (preferably below 50 Torr) and produce better quality fried foods with less oil content when compared with atmospheric frying [3,4]. However, there are still some disadvantages related to VF process. This operation is extremely time and energy consuming, especially at low frying temperature. The oil content in fried products need to be reduced considering the demands of consumers. The color, shape, taste, nutrient content and many other quality parameters of samples are subjected to change because of long term exposure to oil temperature. Considering the problems highlighted above, it seems necessary to search for innovative frying technique that will allow to obtain good quality dried products with higher production efficiency.

One of the recommended ways to overcome the limitations of vacuum frying is application of hybrid methods, where the energy is provided alternatively by combination of different energy sources [5]. Microwave (300 MHz and 300 GHz) can heat dielectric materials by inducing molecular vibration as a result of dipole rotation or ionic polarization [6]. By absorbing the microwave energy, the mass transport is more effective compared to conventional methods and results in shortening of drying time [7]. Bai-Ngew et al. [8] investigated the microwave vacuum-drying of durian chips with different microwave power density levels, and found that the increase in the microwave power intensity produced a clear increase in the drying rate. Łechtańska et al. [9] suggested that convective drying assisted with both microwave and/or infrared radiation significantly shortened the drying time, allowed better preservation of vitamin C content, improved the color of the product, and saved energy consumption compared to pure convective drying. The application of microwave in VF (microwave-assisted vacuum frying) is reported to accelerate the dehydration process

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Table 1
Experimental design of frying programs and the effective moisture diffusivity (m^2/s) of every frying process.

Frying process	Frying temperature (°C)	Vacuum degree (kPa)	Ultrasound power (W)	Total Microwave power (W)	Time to complete the frying (min)	D_{eff} (m^2/s)
VF	90	10	0	0	16	0.764×10^{-8}
US600VF	90	10	600	0	14	0.898×10^{-8}
US600M600VF	90	10	0	1800	10	1.224×10^{-8}
US600M800VF	90	10	600	2400	10	1.393×10^{-8}
M800VF	90	10	0	2400	10	1.218×10^{-8}
US300M800VF	90	10	300	2400	10	1.308×10^{-8}
US600M800VF	90	10	600	2400	10	1.393×10^{-8}

VF = vacuum frying; M = Microwave; US = Ultrasound.
The total microwave power used W = (600 or 800) * 3;
Time to complete frying was when the moisture was less than 0.04 kg/kg solids.

and produce fried fruits and vegetables with lower oil content, improve texture and flavor characteristics [10,11]. The potentially increased application of microwave in the vacuum frying is based on the fact that frying occurs under lower frying temperature, therefore, is more efficient and the fried product is of high quality.

Ultrasound assisted dehydration has been a topic of interest for many years. Ultrasound is a mechanical wave with a frequency range of 20 kHz to 10 MHz and could propagate in gas, liquid, and solid media [12]. The low frequency, high energy, power ultrasound in the kHz range could break cellular structures, activate and inhibit chemical and physical alterations in food, and produces a number of effects which lead to the intensification of mass transfer-based process [13]. The cavitation produced by high intensity acoustic waves causes heating and micro-vibration effects [14], and facilitates the removal of strongly bound moisture more effectively during dehydration [15]. Other effects associated with ultrasound such as sponge effect [16], microstreaming [13], and formation of microscopic channels [17] also help enhance the mass transfer. For example, Santacatalina et al. [18] reported that the application of power ultrasound shortened the convective drying time by 77% when apple samples were dried at low-temperature (−10, −5, 0, 5 and 10 °C). An application of ultrasound at 75 W power level at −10 °C shortened the convective drying time by 80.3% [19]. The ultrasound application may overcome some of the limitations of convective drying by increasing the drying rate at lower temperatures and so, the mass transfer phenomena [20].

In addition, the combination of microwaves and ultrasound had been reported to enhance the dehydration process and improve the quality attributes of dried fruits and vegetables. Szadzińska et al. [5,21] reported that combination of ultrasound and microwave in a convective drying process significantly shortened the drying time, reduced the energy consumption and improved the quality parameters of green pepper and strawberries. Kowalski et al. [22] reported an improvement of the drying kinetics as well as the energy utilization during air drying of raspberries when ultrasound and microwave were combined. The combination of ultrasound and microwave also significantly lowered the degree of shrinkage, better retained the fresh-like color, aroma and bioactive compounds [19,23].

Although there are a lot of researches regarding the combination of high power ultrasound and microwave in drying processes to accelerate dehydration process, the application of ultrasound and microwave, in combined form has rarely reported in the vacuum frying. Thus, this work was aimed at combination of ultrasound and microwave, with different power levels, in the vacuum frying system to increase the process efficiency and improve the quality of fried foods. Purple-fleshed potato were used as test specimen and experiments were conducted using a hybrid vacuum frying process with different microwave and ultrasound power levels, and a conventional vacuum frying (VF) as reference. The enhancement of vacuum frying process by the application of combined ultrasound and microwave was evaluated using moisture evaporation kinetics, dielectric properties, the variation of water status, surface temperature during the process. Quality attributes containing oil uptake, texture, shrinkage, color, water activity and total anthocyanin of the fried purple-fleshed potato chips were also comparatively studied. The microstructure of fried samples was comparatively observed using the scanning electron microscope (SEM).

2. Materials and methods

2.1. Material and apparatus

The purple-fleshed potato (*Ipomoea batatas L.*) and palm oil (by Yihai Kerry Company, Shanghai, China; 24°), used in this study, were purchased from a local market in Wuxi, China. The average initial water content of the fresh purple-fleshed potato samples was 70.31 ± 1.16 (g water/100 g total) as measured by the oven drying method [24]. Fresh purple-fleshed potatoes were washed, peeled and sliced (30 ± 1 mm diameter and 4 ± 0.2 mm thick) using a circular cutting mold. Then, the slices were blanched at 90 °C for 3 min, cooled under running tap water for 1 min to remove excess starch [25] and then wiped dry using an absorbent paper. These slices were fried to a final moisture content below 0.04 kg water/kg solid.

Table 1 shows the experimental design which contains different frying treatments including vacuum frying (VF) as a reference. For this purpose a laboratory scale ultrasound and microwave combined vacuum frying apparatus was designed and built. The schematic diagram of the ultrasound microwave-assisted vacuum frying instrument is presented in Fig. 1. The frying vessel (15 L oil) was made of polytetrafluoroethylene (PTEF), a material that does not absorb microwave energy and it is stable at high temperature (up to 150 °C) [26]. Three microwave devices (Aorun Microwave Industry Co., Ltd, Nanjing, China) were used as the heating source. They were uniformly located around the vacuum chamber and served as heating source of the equipment. The maximum power output of each microwave device was 1000 W and operated at the frequency of 2450 MHz. The ultrasound system consisted of five ultrasound devices (Aorun Microwave Industry Co., Ltd, Nanjing, China) located along the bottom of the frying vessel. The frequency of the ultrasound devices was 28 kHz and their power could be varied from 0 to 600 W. This fryer was also equipped with a centrifuge (Taibang Electromotor Industry Co., Ltd, Zhejiang, China) to remove the surface oil of products after deep frying at a high rotational speed (370 rpm). The vacuum breaking switch was turned on after the de-oiling process to maintain the same speed of air current in every frying process. The control system of the fryer helps the control and measurement of process parameters, including frying oil temperature, microwave and ultrasound power, the vacuum level and the rpm of centrifuge and the total energy consumption, on-line.

2.2. Methods used for frying

The vacuum frying (VF) experiments were carried without using the ultrasound and microwave devices as a reference. A batch of 50 g purple-fleshed potato was fried in 5 L of palm oil at relatively low frying