Effects of preliminary treatment by ultrasonic and convective air drying on the properties and oil absorption of potato chips

Jin Zhang \textsuperscript{a}, Liuping Fan \textsuperscript{a,b,*}

\textsuperscript{a} State Key Laboratory of Food Science & Technology, Jiangnan University, 1800 Lihu Avenue, Wuxi, Jiangsu 214122, China
\textsuperscript{b} School of Food Science and Technology, Jiangnan University, 1800 Lihu Avenue, Wuxi, Jiangsu 214122, China

\textbf{A R T I C L E    I N F O}

\textbf{Keywords:}
- Water content
- Frying
- Oil absorption
- Texture
- Color change
- Microstructure

\textbf{A B S T R A C T}

The initial water content was closely related to the oil absorption and properties of fried food. The effects of convective air drying (D) and ultrasound combined convective air drying (UD) pretreatment on the properties and oil absorption of potato chips have been investigated. The oil contents were $48.48 \pm 1.42\%$ and $39.78 \pm 3.08\%$ for control samples (without D and UD pretreatment) and ultrasound treated samples (without D pretreatment). When the mass loss of samples was reached the proportion of quality to without drying samples quality $80\%$, $50\%$, and $20\%$, the oil contents of D pretreated samples decreased by $12.67\%$, $28.24\%$ and $62.07\%$, respectively, and the oil contents of UD pretreated samples decreased by $7.42\%$, $24.10\%$ and $51.76\%$ (compared to the ultrasound pretreated samples), respectively. By applying ultrasound before frying, more cracks and pores were exhibited of fried potato chips. After drying process, potato chips exhibited less disruption of cell structure and less deformation of cell irregular. The hardness of the D and UD pretreated potato chips increased with the extension of drying. The FTIR analysis stated the formation of amylose-lipid complexes. This research could contribute to providing evidence for the development and application of the pretreatment strategies.

\section{1. Introduction}

Frying has been widely applied in the food industry as a traditional food processing method, and it was considered to be the most popular way. Potato chips have been generally employed as a typical model of fried food [1]. It has shown that water evaporation as well as oil absorption occurred during frying, which resulted in crispy taste property of potato chips. The whole frying processing was related to a series of physical and chemical changes, including protein denaturation, starch gelatinization, Maillard reaction, caramelization, and so on, thus the potato chips have a special flavor [2-4]. Due to its unique aroma and crispy texture of potato chips, it has become the most popular snack for ordinary customers [5]. However, at present, the excessive oil content of potato chips was a major concern for consumers, because it is well known that the consumption of food high in fat could have an unfavorable influence on people’s healthy [6,7]. Therefore, it is significant and indispensable in reducing oil absorption for potato chips.

Previous studies have been found that many factors were associated with oil absorption, including frying conditions, initial moisture content, material compositions, food surface roughness, pore size distribution, and so on, and these results play important pares in reducing oil content of fried foods [2,8-12]. Many excellent pieces of research were dedicated to the viable and sustainable mitigation methods in reducing oil absorption of potato chips. Previous studies have reported that the preliminary treatment process before frying was an effective strategy for reducing the oil content of fried foods [13]. From current works of literature, these pretreatment methods before frying could be broadly divided into two types namely: traditional pretreatment technologies and innovative pretreatment technologies [14]. The traditional technologies refer to old and common technologies, which have been extensively used in the field of the food frying industry, including convective air drying, blanching, coating, and osmotic dehydration [15-17]. While innovative technologies have been developed to improve the properties and quality of fried foods, including ultrasound, irradiation, pulsed electric fields, and high-pressure processing [18,19]. As a simple and convenient dehydration method, convective air drying is efficient to reduce water content and shorten the effective drying time, and it is one of the most widely preliminary treatment technologies in reducing oil absorption of potato chips [20]. The application of ultrasound in food processing has been conducted to have better product yields, lower processing time, lower maintenance costs, and better quality properties [21]. As a green food process method, the application of ultrasonic prior
to frying is beneficial for decreasing the oil content of fried food. Oladejo et al. [14] found that ultrasound pretreatment had decreased by 65.11% and 71.47% in the oil content of fried sweet potato at the frying temperature of 150 and 170 °C, respectively. Mohammadalinejhad and Dehghannya [22] also demonstrated that ultrasound treatment before deep-fat frying could be an effective way to reduce oil uptake of potato strips.

As described above, most of the researches reported in the literature have focused on that the effect of a single pretreatment method on the quality and oil content of potato chips. Hence, more works need to be done about studying the effects of combining different pretreatment on the characteristics and the oil absorption of potato chips. The primary aims of this study were: (1) to investigate the effect of single pretreatment (ultrasound or convective air drying) on the characteristics and oil uptake of potato chips; (2) to analyze the effect of combined pretreatment (ultrasound and convective air drying) to the characteristics and oil uptake of potato chips; (3) to determine whether the combined pretreatment will be conducive to the properties of frying potato chips. The research of the combination of conventional pretreatment technologies and innovative pretreatment technologies of potato chips could provide evidence for the development and application of the pretreatment strategy.

2. Materials and methods

2.1. Materials

Potatoes (Solanum tuberosum) used in this study were obtained from a local supermarket in Wuxi, China, and the main chemical composition included starch content of 12.26 ± 0.89%, moisture content of 80.48 ± 1.35%, protein content of 2.2 ± 0.42%. The specific gravity of potatoes is 1.05 ± 0.05 g/cm3. Palm oil (Jiali Co. Ltd., Shanghai, China) was chosen as frying oil. Vitamin E worked as an antioxidant at the palm oil, and its addition level was approximately 200 ppm.

2.2. Sample preparation

Potatoes were selected, washed, peeled, and sliced with a thickness of 2 ± 0.3 mm and a diameter of 22 ± 0.3 mm. Distilled water was used to wash out the starch of potato slices. Then the potato slices were blanched for 3 min in boiling water with the ratio of 1:8 (sample/water, g/g). These slices were taken out and cooled in cold water, and the absorbent paper was used to remove the excess moisture on the surface of the samples. All potato slices were weighed and samples with a weight of 0.85 ± 0.05 g were chosen for various tests.

2.3. Pretreatment procedure

Convective air drying (D) and ultrasound combined convective air drying (UD) were used as a pretreatment before frying. As shown in Fig. 1, the design of experiments contained different pretreatment. The ultrasound pretreatment was carried out by the method applied in our previous study [23]. Potato slices were pretreated using a 360 W power level below 30 °C for 120 min.

Ultrasonic pretreated slices and the control (without ultrasonic pretreated slices) blanched in boiling water for 3 min [24]. The convective air drying of potato slices was carried out in an electric thermostatic drying oven (GZX GF101, Yuejin Medical Equipment Co., Ltd, Shanghai, China), and those samples were dried at 60 °C. During drying, the mass loss of samples was detected in succession until it arrived the proportion of quality to without drying samples quality 80%, 50%, 20%. As shown in Fig. 1, these samples were designated as D80, D50, D20 (without ultrasonic pretreated samples), and UD80, UD50, UD20 (ultrasonic pretreated samples). In addition, ultrasound pretreated slices and without ultrasonic pretreated slices were designated as UD100 and D100 (without drying). All experiments were carried out three times.

2.4. Frying process

The prepared samples were put into an electric-heated thermostatic controlled fryer (Jingda Equipment Manufacturer, Jintan, China), and the ratio of potato slices to oil was 1:50 (g/mL). Potato chips were fried at 180 °C until all samples showed low water content (below 2.5%, wb). These fried samples were taken out of the fryer, placed on a wire mesh, and statically cooled to room temperature for subsequent measurement. The experiment was always performed with fresh oil. After frying, the samples were kept in seal and stored at normal temperature, and in a cool, ventilated, dry place, avoid direct sunlight.

2.5. Water content and water status determined of pretreated samples

Considering that the higher water content in some pretreated samples, the water content and water status of control samples and pretreated samples were immediately examined after pretreatment.

The moisture content of the pretreated samples was determined by the oven method [25]. Approximately 10 g of pretreated potato slices was put in a hot-air oven (Binder, Germany) at 105 °C until a constant-weight was reached. The moisture content was expressed by the wet basis (wb) of the samples.

The water status of pretreated potato slices was determined by the

Fig. 1. Experimental design of pretreatment process.
methods of Wang et al. [26] with minor modification. The low-field nuclear magnetic resonance instrument (MesoMR23-060H-I, Shanghai Niumai Corporation, China) was used to determine the water status of pretreated potato slices with the frequency fields of 23.3 MHz at 32.00 °C. The magnet strength was 0.5 T. The pretreated potato slices were put in a coil with a diameter of 25 mm. Carr-Purcell-Meiboom-Gill (CPMG) sequence was used to determine the spin-spin relaxation time (T2) spectrum and peak relative areas (A2). Each measurement was conducted three times.

2.6. Oil contents and oil distribution measurement of potato chips

The oil content of fried potato slices was investigated by the Soxhlet extraction method with petroleum ether (60–90 °C) as a solvent [1]. The dry basis (db, g/g) was used to weigh the oil content of fried samples. The oil distribution at the macro level of fried potato chips was investigated by the method of Yang et al. [27] with little modification. Oil distribution of entire potato chips was observed using magnetic resonance imaging (MRI). The T2-weighted images were obtained by the low-field nuclear magnetic resonance instrument (MesoMR23-060H-I, Shanghai Niumai Corporation, China). The parameters of typical pulse were as follows: TE = 20.0 ms, TR = 500.0 ms, Slices width = 5.0 mm, Slices = 1, Slice gap = 1, Average = 2.

The oil distribution in micro level of potato chips was measured according to the method of Zhang et al. [28] with minor modification. Oil distribution in the center of the fried sample was obtained by confocal laser scanning microscope (CLSM). The stained oil with Nile Red was used to be the fering medium, and the potato slices were fried according to the 2.4 section. Fried samples were observed in fluorescein mode at 514 nm with the Ar laser, and the 10× magnification objective lens was used. The 3D reconstruction images of these fried samples were obtained by the Carl Zeiss LSM software (ZEN 2012).

2.7. Texture and color measurement of fried samples

These fried potato chips were evaluated by a texture analyzer (TA-XT2i, Stable Micro System Co. Ltd., Surrey, UK). One sample was pleased on the hollow cylindrical base, and the ball probe (P/0.25 s) traveled at 5 mm/s until it punctured the sample. At least 10 samples from each pretreated potato chip were tested. The hardness of potato chips was measured and the unit was newton (N).

The color of fried chips was determined by the Chroma Meter (CM-2003d, Konica Minolta, Japan). The measurement was done on the surface of potato chips and ten replicates of measurements were performed. The color parameters of sample were described as \( L^* = 0 \) (black); 100 = white), \( a^* \) (\( a = \) greenness; \( a = redness \)), and \( b^* \) (\( b = blue\)-ness; \( b = yellowness \)). Spectrophotometer has been calibrated with a standard whiteboard before the color testing.

2.8. Fourier-transform infrared spectroscopy (FTIR) analysis

All fried potato chips were grounded into powder, then these powders were defatted according to the method described by Bligh and Dyer [29]. The defatted powder (2 mg) was mixed with solid KBr power (200 mg), and then the mixed powder (10 mg) was made into KBr pellet. These pellets were analyzed by a spectrometer (Thermo Scientific, Niclolet iS10, MA, USA) and the spectra were recorded from 4000 to 400 cm\(^{-1}\) [30].

2.9. Examination of microscopic structure

The microscopic structure of fried samples was observed by scanning electron microscopy (SEM, Quanta 200, FEI Company, Holland). Fried potato chips were defatted by the soxhlet extraction method (Section 2.6). The defatted potato chips were coated with a thin gold layer. Then these samples were observed in a relatively low acceleration voltage (3.0 KV). The images of all samples were obtained at 30× magnification, 100× magnification, and 200× magnification.

2.10. Statistical analysis

All experiments were tested in triplicate. SPSS software for Windows (SPSS v19.0, IBM, USA) and Origin 8.0 (Microcal Software, Inc., Northampton, USA) were used to analyze data. The data are expressed as the mean values ± standard deviations. The difference among the average values was considered significant at a 95% confidence level (p < 0.05).

3. Results and discussions

3.1. Water content of pretreated slices

The influence of pretreatment on the water content of potato slice (before frying) was exhibited in Fig. 2. Ultrasonic pretreated slices and the control (without ultrasonic pretreated slices) were dried until the proportion of quality to without drying samples were 80%, 50%, 20%, respectively. The pretreatment of convective air drying had a significant effect on the water content of the potato slices before frying (p < 0.05). As expected, a significant decrease in water content occurred during the convective air drying process. Additionally, there showed no significant difference between D100 and UD100, D80 and UD80, D50 and UD50, D20 and UD20, indicating that the application of ultrasonic before convective air drying has no significant effect on water content when they have the same proportion of quality to without drying samples. During the convective air drying process, the free water of potato slices was removed efficiently [31]. In the previous study, ultrasound treatment showed no effects on free water status [23]. Thus, the ultrasonic application before convective air drying could have no influence on the changes in water content.

3.2. Water status of pretreated slices

Fig. 3 showed the effects of D and UD pretreatment on the spin-spin relaxation time (T2) spectrum and peak relative areas (A2) of potato slices before frying, which can reflect the characteristics and the quantitative changes of the water status. The water status could be classified into three general types: bound water, mechanical bound water, and free water [14]. T21 and A21 (0.1–1 ms) mainly represent bound water, which has the highest binding energy and lowest mobility among the three water status. T22, A22, and A23 (1–50 ms) indicate mechanical bound water, which shows a lower binding energy and higher mobility than that of bound water. T24 and A24 (50–1000 ms) represent free water, which has the lowest binding energy and highest mobility among three water status [32,33]. As can be found from Fig. 3(a), the value of T2 and A2 of all D pretreated samples showed a significantly difference (p < 0.05). The T2 values of all D pretreated samples, including T21, T22, T23, and T24, were decreased with the extension of the drying process, moreover, the D20 samples had lost the whole free water (T24) and partial mechanical bound water (T23). It indicated that the freedom degree of three types of water decreased. The A21 values increased significantly (p < 0.05) during convective air drying, and the values of the sum A22 and A23 increased. It was suggested that the relative area of bound water and mechanical bound water raised. Obviously, the A24 values reduced significantly (p < 0.05) with the extension of convective air drying, and the D20 samples had no value of A24, indicating the D20 samples contained no detectable free water.

As shown in Fig. 3(b), the UD pretreated potato slices had a significant difference in the values of T2 (T23, T22, T21, and T24) and A2 (A21, A22, A23, and A24). It was obvious that the UD pretreated samples and D pretreated samples showed a similar variation trend in the T2 and A2 values. It might be due to the ultrasound pretreatment do not affect binding energy and mobility of water. While convective air drying
pretreatment had a marked effect on water status. The ratio of free water and mechanical bound water decreased, while the proportion of bound water increased with the extension of the drying process. The result was correspondent with the change of water content during D and UD pretreatment. Consistent results were reported by Jiang et al. [34], who obtained the water status variation regular pattern in microwave freeze-drying.

### 3.3. Oil absorption of potato chips

#### 3.3.1. Oil content

Fig. 2 shows the dry basis oil content of fried potato chips after D and UD pretreatment. The oil contents were 48.48 ± 1.42% and 39.78 ± 3.08% for D100 and UD100 samples, respectively, indicating the UD pretreatment led to a significant decrease in oil content (p < 0.05). For D pretreated samples, the potato slices were dehydrated preliminary by the convective air drying process, and then they were fried. The drying pretreatment reduced the oil content of fried potato chips. When the mass loss of potato slices was reached the proportion of quality to without drying samples quality 80%, 50%, and 20% (D80, D50, D20 samples), the oil contents decreased by 12.67%, 28.24%, and 62.07%, respectively. The decrease in oil content was in good agreement with previous works [35,36].

The oil absorption also decreased with the extension of the dehydration for UD pretreated potato slices. When the mass loss of ultrasound pretreated samples was reached the proportion of quality to without drying samples (ultrasound pretreatment) quality 80%, 50%, and 20% (UD80, UD50, UD20 samples), the oil contents decreased by 7.42%, 24.10% and 51.76%, respectively, compared with ultrasound pretreated samples (UD100). For UD pretreated potato chips (UD80 and UD50) the oil uptake was significantly smaller than for D ones (D80 and D50) (p < 0.05). The results presented the synergetic effect of combining ultrasound pretreatment and convective air drying on decrease oil absorption. Interestingly, when the mass loss of samples was reached the proportion of quality to without drying samples quality 20%, the oil content was no significant difference (p < 0.05) between D20 potato chips and UD20 potato chips. The results indicated that the pretreatment method with ultrasonic before drying did not affect the oil absorption when the potato slices were dried to lower moisture content (below 20%).

Comparison between two pretreatments of potato chips (D and UD pretreatment) with the same water content level showed that potato chips pretreated by UD obviously decreased oil content compared to the D pretreated samples. The reasons that this kind of phenomenon appeared were as follows: during pretreatment, gas bubbles produced, contracted, expanded, and implode in the medium (water), which was called as “cavitation phenomenon” [37]. When the cavitation phenomenon occurred near the surface of potato slices, it disrupted samples outer by the generation of extreme heat, extremely high pressure, and sheer force [38]. Meanwhile, the compression and rarefaction of the ultrasound waves alternated during ultrasound pretreatment, which was called as “sponge effect”. The sponge effect can lead to different pressure in the structure of samples, which developed microscopic channels by disrupting cellular and forming larger cavities [31]. This can provide an easier water removal path and accelerate the mass transfer during the subsequent processing. During the frying process, the creation of higher vapor pressure resulted from the enhance in moisture migration. The higher vapor pressure inside the samples could prevent the oil penetration of samples [39]. This was the possible reason why the UD pretreated samples have less oil absorption after frying.

In general, the results of oil absorption showed that both D pretreated samples and UD pretreated samples demonstrated a decreasing trend in oil absorption. The reasons for the decrease in the oil absorption of D pretreated samples could be summarized as follows: (1) the initial moisture of D pretreated samples decreased prior to frying, and low initial moisture of potato slices can lead to less oil absorption in final potato chips. (2) an external crust formed after D pretreatment, which can resist oil infiltration of potato chips during frying. (3) a compact structure of potato slices generated due to D pretreatment, and it was not conducive to the oil uptake.

#### 3.3.2. Oil distribution at the macro view

The oil absorption of D and UD pretreated potato chips was observed by using MRI to monitor the oil macroscopically distribution at various zones. The signal intensity of MIR is strongly affected by oil content in different regions of samples, and the MIR images can visually provide oil distribution of the whole samples [40]. As shown in Fig. 5, the color bar on the right represented a relative scale for the oil content of samples. The red color indicated the presence of the areas with the higher oil content, while the blue color was associated with the lower oil content [1]. The pseudo color images (Fig. 5) reflected the oil macroscopically distribution of potato chips with D and UD pretreatment. It was quite obvious that color spatial distribution has changed in the samples with different pretreatment conditions. The trend of oil absorption of samples
with different pretreatments was basically consistent with the results shown in Fig. 4. With the intensity of drying pretreatment, the D pretreated samples represented dramatic changes from green to blue in the center part of potato chips (D100, D80, D50, and D20), suggesting a significant reduction in oil absorption. Lots of researches showed that oil absorption was closely related to the water content [12,41,42]. During the drying process, the moisture on the sample surface evaporates first, and then the moisture inside the sample was gradually lost. Compared with D100, the D80 sample has a large blue area in the center, which was probably related to the evaporation of surface water after short-time drying. D50 and D20 samples have more blue area in the center and edge, which was probably related to the migration and evaporation of surface and internal water after long-time drying.

For UD pretreated samples, there are similar trends with the D pretreated samples in the changes of oil distribution. With the reduction of the water content, green areas of potato slices were gradually replaced by the blue area, which was related to the reduction of oil content. Compared with the D pretreated samples (D100, D80, and D50), the UD pretreated samples (UD100, UD80, and UD50) exhibited lower oil distribution. The application of ultrasound pretreatment before frying could help to reduce oil absorption of potato chips. This result was consistent with the previous study [23]. While compared with D20 sample, the UD20 sample did not show less oil uptake after frying. That might be due to the effect of ultrasound was not significant at the low water content of samples. Compared with the ultrasound pretreatment, the effect of initial moisture content was more remarkable. It is

Fig. 3. Effects of pretreatment on water status of potato slices before frying. The different capital letters indicate significant differences among samples (p < 0.05).
interesting to observe that the edge part has higher oil content compared with the center part of all samples, which might be related to the highly porous structure in the edge layer of potato chips. This phenomenon was in accordance with the reports in the literature [43,44].

3.3.3. Oil distribution at the micro view

Oil microscopically distribution in the center of the D and UD pretreated potato chips was further investigated by using CLSM. Fig. 6 illustrated a considerable variation in varying oil microscopically distribution of potato chips with different pretreatments. The red areas referred to the oil presence, while the black regions represented the oil absence. The D100 and UD100 samples showed the largest red regions of all samples, indicating that the oil was covered the cell surfaces and filled the cell interstitial. Samples that were pretreated with D exhibited a decrease in red zones with the extension of the dehydration. When the mass loss of D pretreated samples was reached the proportion of quality to without drying samples quality 80%, 50%, and 20% (D80, D50, D20 samples), the oil microscopically distribution showed a clear downward trend. It was also observed from the figure that the oil microscopically distribution of UD pretreated samples decreased. The less oil penetration was clearly evident in the growth of black zones in UD80, UD50, and UD20 samples. The reduction in oil microscopically distribution for D and UD pretreated samples was in line with the results of oil content and NMR. As can be noted, D100 and UD100 potato chips seemed to accumulate the most oil distributed along the contours of cells and adhered to the cell wall, which accumulated in bigger continuous domains, compared to the potato chips that were pretreated by convective air drying. While oil was mainly distributing of inside the intercellular spaces with the extension drying. This might be related to the changes in the cell structure when the moisture evaporating during the drying [45]. Oil distribution at the micro view of potato chips has good agreement with oil content and oil distribution at macro view results.

3.4. Textural properties of potato chips

Among textural properties, crispness is a substantial and important index of fried products, and it is closely related to the rapid fracture under stress at small strains. The maximum force achieved before the fracture is called hardness. Crispness is a quality of brittle materials that rapidly fracture under stress at small strains. A brittle object will exhibit a large hardness [46]. Lots of researches showed that the hardness was negatively related to the crispness [45,47]. The influence of D and UD pretreatment on the maximum breaking force of fried potato chips was studied. Table 1 showed the hardness of potato chips with different
rupture the potato chips. The reports which applied ultrasound in the food product showed harder simply due to its denser structure [46]. Moreover, the apparent density in comparison to D pretreated samples [22]. Thus the UD pretreated potato slices exhibited lower sonic pretreatment. It was obvious that the value of hardness of D pretreated potato chips changed with the extension drying, indicating the amount of force required to break the D pretreated samples differed. Compared with the control samples (D100), the hardness of D pretreated potato chips with the moisture content level of 80%, 50%, and 20% increased by 19.15%, 32.33%, and 66.43%, respectively. This might be related to the generation of a compact structure of potato slices generated during D pretreatment. It was demonstrated that the convective air drying process allowed increasing the values of L* and a* of UD pretreated potato chips, and it had no effect on the b* values of the UD pretreated potato chips, and it had no effect on the b* values of the D pretreated potato chips. It was demonstrated that the convective air drying process allowed increasing the values of L* and a* of UD pretreated potato chips, and it had no effect on the b* values of the UD pretreated potato chips (p < 0.05). Remarkable that there was no difference in the values of L*, a*, and b* between D pretreated samples and UD pretreated samples with the same water content level, indicating the pretreatment of combining ultrasound and convective air drying prior to frying did not cause adverse effects on color characteristics.

3.5. Color parameters of potato chips

The color characteristics of D pretreated and UD pretreated potato chips were shown in Table 1. For the relatively long drying time, the values of L* and a* increased slightly of D pretreated potato chips (p < 0.05). There showed no significant difference in b* values of D pretreated samples with different moisture content level (p < 0.05). The effect of UD pretreatment on color parameters of samples was similar to that of the D pretreated potato chips. It was demonstrated that the convective air drying process allowed increasing the values of L* and a* of UD pretreated potato chips, and it had no effect on the b* values of the UD pretreated potato chips (p < 0.05). The different capital letters in column indicate significant differences among samples (p < 0.05).

### Table 1

| Samples   | Hardness (N) | L*       | a*       | b*       |
|-----------|--------------|----------|----------|----------|
| D100      | 502.49 ± 22.37A | 66.55 ± 1.16A | 1.69 ± 0.08B | 27.68 ± 0.78AB |
| D80       | 598.70 ± 26.05A | 65.84 ± 0.99A | 2.45 ± 0.26A | 26.63 ± 0.90A |
| D50       | 664.95 ± 16.40C | 64.21 ± 0.84B | 2.13 ± 0.19B | 27.40 ± 1.64AB |
| D20       | 836.28 ± 28.59D | 63.89 ± 1.55B | 4.54 ± 0.26C | 28.64 ± 1.52B |
| UD100     | 360.71 ± 22.96C | 67.52 ± 0.70B | 1.36 ± 0.07B | 27.93 ± 0.91AB |
| UD80      | 470.08 ± 8.42B  | 62.86 ± 1.24C | 2.50 ± 0.15B | 26.56 ± 0.96A |
| UD50      | 554.96 ± 21.66G | 63.06 ± 1.32B | 2.68 ± 0.20B | 28.30 ± 0.67AB |
| UD20      | 730.60 ± 28.66H | 60.77 ± 1.04B | 4.20 ± 0.13C | 28.29 ± 1.74B |

Table 1 Effects of pretreatment on hardness and color of potato slices after frying.

As shown in Fig. 7, the interaction between oil and starch was conducted by FTIR spectra. In contrast to the potato starch, the FTIR spectra for both the defatted samples with D pretreatment and the defatted samples with UD pretreatment exhibited obvious two extra peaks at 2854 cm⁻¹ and 1764 cm⁻¹. The peak at 1764 cm⁻¹ was attributed to the vibration of carbonyl and the asymmetric stretching vibration of –CH₂ and –CH₃ in fatty acids was positioned at the peak of 2854 cm⁻¹ [50,51]. The vibration of carbonyl might be related to the formation of amylose-lipid complexes [52]. Besides, the absorption peak of the UD pretreated samples was stronger than that of the D pretreated samples at the peak of 1764 cm⁻¹, which indicated that UD pretreated samples bound more fatty acids or fatty acids esters than D pretreated samples during the frying process. This might result in the variation of microstructure after ultrasonic pretreatment. The formation of pores, cracks, and micro-channels was conducive to the bound of amylose and lipid. While how amylose and lipid bond to each other and how the pretreatment affects the amylose–lipid complexes need to be further studied.

3.6. FTIR analysis

By application of ultrasound in the drying process had a decreasing effect on the breaking force of raspberries [49]. A similar result was found by other research the vacuum frying process, reduced the hardness of fried purple-fleshed potato chips [48]. The color characteristics of D pretreated potato chips were shown in Table 1. For the relatively long drying time, the values of L* and a* increased slightly of D pretreated potato chips (p < 0.05). There showed no significant difference in b* values of D pretreated samples with different moisture content level (p < 0.05). The effect of UD pretreatment on color parameters of samples was similar to that of the D pretreated potato chips. It was demonstrated that the convective air drying process allowed increasing the values of L* and a* of UD pretreated potato chips, and it had no effect on the b* values of the UD pretreated potato chips (p < 0.05). The color characteristics of D pretreated and UD pretreated potato chips were shown in Table 1. For the relatively long drying time, the values of L* and a* increased slightly of D pretreated potato chips (p < 0.05). There showed no significant difference in b* values of D pretreated samples with different moisture content level (p < 0.05). The effect of UD pretreatment on color parameters of samples was similar to that of the D pretreated potato chips. It was demonstrated that the convective air drying process allowed increasing the values of L* and a* of UD pretreated potato chips, and it had no effect on the b* values of the UD pretreated potato chips (p < 0.05). Remarkable that there was no difference in the values of L*, a*, and b* between D pretreated samples and UD pretreated samples with the same water content level, indicating the pretreatment of combining ultrasound and convective air drying prior to frying did not cause adverse effects on color characteristics.
3.7. Microstructure of potato chips

The characterization of microstructural changes of D and UD pretreated potato chips at the frying temperature of 180 °C was observed with SEM. Fig. 8 exhibited the scanning electron micrographs (30×, 100×, and 200× magnification) of the surface changes of fried potato slices induced by D and UD pretreatment. In the D pretreated samples (D100 and D50), the surface showed obvious defects of contraction dent, warpage, and rough. While the surface of UD pretreated samples (UD100 and UD50) embossed slightly. Remarkable that the UD pretreatment resulted in more pores and microscopic channels on the surface as compared to the D pretreatment samples with the same water content level, which was related to the “sponge effect” of ultrasonic wave [53]. By applying ultrasound before frying, more cracks and pores were exhibited of potato chips, which led to easier water evaporation. The dried area moved from the sample surface to the interior with a constant speed, thus the fractures and shrinkage of cells were not serious. Rodríguez, Santacatalina [54] also illustrated that the ultrasonic application made easier the moisture pathway by disrupting the cellular structure.

It was worth mentioning that, with the convective air drying treatment before frying, the scanning electron micrographs of potato chips (D50 and UD50) showed less disruption of cell structure and deformation of cell irregular compared with the samples without drying process (D100 and UD100). It could be related to the rate of moisture evaporation. For D100 and UD100 samples, the violent evaporation of moisture occurred during the frying process, which resulted in rapid vapor migration, serious cell ruptures, and severe microstructure fractures [55]. By applying convective air drying prior to frying, a part of the water in potato slices evaporated at a lower temperature (60 °C), and the remaining moisture of samples evaporated during the frying process with a higher temperature (180 °C). The D50 and UD50 samples lost much of their moisture at a lower temperature, and the evaporation of water was not so violently during frying. Thus they exhibited less disruption of cell structure and deformation of cell irregular compared with D100 and UD100 samples.

4. Conclusions

The preliminary treatment including D and UD before the frying markedly affected the properties and oil uptake of potato chips. The moisture content of pretreated potato slices showed a significant decrease during the convective air drying process. The application of ultrasonic before convective air drying had no significant effect on water content and water status of pretreated potato slices. Both D pretreated samples and UD pretreated samples demonstrated a decreasing trend in oil absorption, and the effects of UD pretreatment are more remarkable. The value of hardness of D and UD pretreated potato chips increased with the extension drying, and the hardness of UD pretreated potato chips obviously lower than that of the D pretreated samples in the same
water content level. The convective air drying process allowed increasing the values of L* and a* of D and UD pretreated potato chips. The UD pretreatment resulted in more pores and microscopic channels on the surface as compared to the D pretreatment samples with the same water content level.

Declaration of Competing Interest

All authors declare that they do not have any conflict of interest.

Acknowledgements

The authors acknowledge financial support of the China National Natural Science Foundation (31871840), Bingtuan science and technology project, China (2019AB0027) and the General Project of Modern Agriculture in Jiangsu Province, China (BE2019309), which has enabled us to accomplish this study.

References

[1] C. Wang, et al., Rapid assessment of deep frying oil quality as well as water and fat contents in French fries by low-field nuclear magnetic resonance, J. Agric. Food. Chem. 67 (8) (2019) 2361–2368.
[2] A.A. Afrokeli, L.J. Li, M.O. Ngadi, Microstructural evaluation of deep-fat fried chicken nugget batter coating using confocal laser scanning microscopy, J. Food Eng. 102 (1) (2011) 49–57.
[3] V.M. Karizaki, S. Sahin, G. Summu, M.T.H. Movasain, A. Luca, Effect of ultrasound-assisted osmotic dehydration as a pretreatment on deep fat frying of potatoes, Food Bioprocess Technol. 6 (12) (2013) 3554–3563.
[4] M. Mellemo, Mechanism and reduction of fat uptake in deep-fat fried foods, Trends Food Sci. Technol. 14 (9) (2003) 364–373.
[5] M. Botero-Urbé, et al., Effect of pulsed electric fields on the structural properties that affect french fry texture during processing, Trends Food Sci. Technol. 67 (2017) 1–11.
[6] I.S. Saguy, D. Dana, Integrated approach to deep fat frying: engineering, nutrition, health and consumer aspects, J. Food Eng. 56 (2-3) (2003) 145-152.
[7] W.A.M. van Loon, et al., Identification and olfactometry of French fries flavour extracted at mouth conditions, Food Chem. 90 (3) (2005) 757–766.
[8] H.M. Gamble, P. Rice, J.D. Selman, Relationship between oil uptake and moisture loss during frying of potato slices from c.v. Record U.K. tubers, Int. J. Food Sci. Technol. 22 (3) (1987) 233–241.
[9] M.C. Moreno, P. Bouchon, Microstructural characterization of deep-fat fried formulated products using confocal scanning laser microscopy and a non-invasive double staining procedure, J. Food Eng. 118 (2) (2013) 258–266.
[10] M.C. Moreno, C.A. Brown, P. Bouchon, Effect of surface roughness on oil uptake by deep-fried products, J. Food Eng. 101 (2) (2010) 179–186.
[11] M.C. Moreno, P. Bouchon, J. Benguel, P. Gobron, A. Cuyper, J. Dehghannya, A. Neghadi, F. Pedreschi, Effect of pre-drying on quality of French fries, J. Food Eng. 108 (2011) 347–354.
[12] F. Pedreschi, P. Moyano, Effect of pre-drying on texture and oil uptake of potato chips, LWT - Food Sci. Technol. 38 (6) (2005) 599–604.
[13] M.E. Camine, S. Koub, D.J. Donnelly, Potatoes and human health, Crit. Rev. Food Sci. Nutr. 49 (10) (2009) 823–846.
[14] Y. Xu, et al., Power ultrasound for the preservation of postharvest fruits and vegetables, Int. J. Agric. Biol. Eng. 6 (2) (2013) 116–125.
[15] J. Dehghannya, E.A. Naghavi, B. Ghanbarzadeh, Frying of potato strips pretreated by ultrasound-assisted air-drying, J. Food Process. Preserv. 40 (4) (2016) 583-592.
[16] Y. Zhang, et al., The description of oil absorption behavior of potato chips during the frying, LWT 96 (2019) 119–126.
[17] F. Pedreschi, et al., Color development and acrylamide content of pre-dried potato chips, J. Food Eng. 79 (3) (2007) 786–793.
[18] G. Bingol, et al., Producing lower-calorie deep fat fried French fries using infrared dry-blanching as pretreatment, Food Chem. 132 (2) (2012) 686–692.
[19] B. Ikiz, S. Sahin, G. Summu, Pore Development, oil and moisture distribution in crust and core regions of potatoes during frying, Food Bioprocess Technol. 9 (10) (2016) 1653-1660.
[20] G. Lisinska, G. Goldowska, Structural changes of potato tissue during French fries frying, Food Process. Eng. 30 (2006) 681–697.
[21] B.o. Jia, et al., Oil absorption of potato slices pre-dried by three kinds of methods, Eur. J. Lipid Sci. Technol. 120 (6) (2018) 1700382, https://doi.org/10.1002/ejlt.201700382.
[22] M.L. Miranda, J.M. Aguilara, Structure and texture properties of fried potato products, Food Rev. Int. 22 (2) (2006) 173–201.
[23] Y.s. Su, et al., Improving the energy efficiency and the quality of fried products using a novel vacuum frying assisted by combined ultrasound and microwave technology, Innovative Food Sci. Emerg. Technol. 50 (2018) 148–159.
[24] Y.s. Su, et al., Enhancement of water removing and the quality of fried purplish-fleshed sweet potato in the vacuum frying by combined ultrasound and microwave technology, Ultrasonics. Sonochem. 44 (2018) 368–379.
[25] S.J. Kowalski, et al., High power airborne ultrasound assisted combined drying of raspberries, Innovative Food Sci. Emerg. Technol. 34 (2016) 225–233.
[26] M. Safar, et al., Characterization of edible oils, butters and margarines by Fourier transform infrared spectroscopy with attenuated total reflectance, J. Am. Oil Chem. Soc. 71 (4) (1994) 371–377.
[27] M.D. Guillén, N. Cabo, Infrared spectroscopy in the study of edible oils and fats, J. Sci. Food Agric. 75 (1) (1997) 1–11.
[28] S. Wang, et al., Effect of fatty acids on functional properties of normal wheat and adzuki bean starches: a structural and thermal approach, Food Chem. 190 (2016) 285–292.
[29] Y.s. Su, et al., Ultrasonic microwave-assisted vacuum frying technique as a novel frying method for potato chips at low frying temperature, Food Bioproc. Process. 108 (2018) 95–104.
[30] O. Rodriguez, et al., Influence of power ultrasound application on drying kinetics of apple and its antioxidant and microstructural properties, J. Food Eng. 129 (2014) 21–29.
[31] E.P. Kalogianni, E. Papastephaniadis, Crust pore characteristics and their development during frying of French fries, J. Food Eng. 120 (2014) 175–182.