Effects of ultrasound treatment on the starch properties and oil absorption of potato chips

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\textbf{ABSTRACT}

As a non-thermal processing method, the ultrasound treatment prior to the frying process has been demonstrated with great potential in reducing the oil absorption of fried food. This research aimed to evaluate the effect of ultrasound pretreatment on starch properties, water status, pore characteristics, and the oil absorption of potato slices. Ultrasound probe set with two power (360 W and 600 W) at the frequency of 20 kHz for 60 min was applied to perform the pretreatments. The results showed that ultrasound pretreatment led to the surface erosion of starch granules and higher power made the structure of starch disorganized. Moreover, the fraction of bound water and immobilized water were changed after ultrasonic pretreatment. Pores with the minor diameters (0.4–3 μm and 7–12 μm) were formed after ultrasound pretreatment. The penetrated surface oil (PSO) content, and structure oil (STO) content were reduced by 27.31% and 22.25% respectively with lower power ultrasound pretreatment. As the ultrasound power increased, the surface oil (SO) content and PSO content increased by 25.34% and 12.89% respectively, while STO content decreased by 38.05%. By using ultrasonic prior to frying, the quality of potato chips has been greatly improved.

\textbf{1. Introduction}

Deep-fat or immersion frying was the commonest form of treatment used in the food processing industry and daily cooking. Fried food proved widely prevalent in both developed and developing countries. As an important part of fried food, potato chips were appreciated by numerous consumers due to its unique taste, flavor, and textures [1,2]. As one of the most basic consumption, food must be consistent with the quality of people’s requests. In addition, people pursue eating healthily with the improvement of the standard of living. It is generally known that high oil content and calorie were the main characteristics of fried potato chips, which greatly increase the risk for diabetes, obesity, hypertensive, cardiovascular disease and cancer [3,4]. Therefore, for fried food, reducing oil absorption is undoubtedly becoming an important trend in the research.

Considerable efforts have been made to reduce the oil content of fried potato chips. These researches can be organized into three categories, including the improvement of frying oil [5], coating treatment (hydrocolloid coatings, batter coatings, and bread coatings) [6–9], and improvement of frying process such as blanching, pre-drying, de-oiling after frying, air-frying and so on [10–13]. In recent years, some innovative non-thermal treatments were proved to be more economical and environmentally friendly than traditional treatments, and thus draw more attention, such as irradiation, cold plasma, ultrasound, pulsed electric fields, and high-pressure processing [14,15]. As a non-thermal pretreatment, ultrasound has widely application prospects for the frying process, particularly in reducing oil uptake [16,17]. Some researchers combined ultrasound pretreatment with other processes to improve the quality of fried food. Jalal et al. [18] found ultrasound pretreatment played an assistant role in improving osmotic dehydration before frying, and three stages hybrid ultrasound-osmotic-frying process showed a significant effect on decreasing oil content of fried potato strips. Su et al. [19] studied the combination of ultrasound and microwave in the vacuum frying of fried purple-fleshed potato and found it could reduce oil content by about 16–40%. To the best of our knowledge, reports have mostly emphasized that ultrasound pretreatment or the combination of ultrasound and other technology can reduce oil uptake of fried food. However, little further information about the reason for decreasing oil absorption was discussed.

The starch content of potatoes is 12.6–18.2% (fresh-weight basis), which is a major component of potato chips [20]. Studying the structure and properties of starch during pretreatment could definitely explore the cause of decreasing oil absorption for potato chips. Water content can affect the oil absorption and quality of potato chips [21].

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The water turned into vapors and migrated from the center of the samples to the outside layer at high temperatures during frying [22]. The evaporation of water associated with the water status of potato tubers. Studying water content and water status before frying is very important in oil absorption during frying. Low-field nuclear magnetic resonance (LT-NMR) was extensively applied in analyzing water status [23]. During immersion frying, vapor expanded and steam was released in the inner of potato tissue, leading to the formation of pore systems and the accumulation of pore channels [24]. Pore network play an important role in the oil absorption and quality of potato chips. Many measurements and techniques have been adopted to probe pore characteristics, and mercury intrusion porosimetry (MIP) has been widely used as a reliable method to investigate the pore properties of potato chips [25].

So far as we know, there have been few reports in the change of structure and properties of ultrasound pretreated starch before frying. In this research, two ultrasound conditions were selected as the pretreatment before frying, and the main objectives were: (1) to research the effects of pretreatment on granules morphology and properties of potato starch; (2) to investigate the influence of ultrasound pretreatment on water status and pore characteristics of potato slices. (3) to make an assay of the pore characteristics changes, the oil content, and oil fractions of potato chips with ultrasound pretreatment and without pretreatment. Increasingly, the food industry is paying more attention to process optimization and quality manipulation. Therefore, it is significant to investigate the quality and starch properties of potato chips affected by ultrasound pretreatment, and these results could provide scientific guidance for the applications of ultrasound treatment in the food industry, particularly in producing fried food with low fat.

2. Materials and methods

2.1. Preparation of raw potato samples and reagents

Potatoes (Solanum tuberosum L, Helan15 variety) used in this study were bought from a market in Wuxi, China, and the main chemical composition included starch content of 12.26%, moisture content of 80.48%, protein content of 2.2%. The potato samples were selected, cleaned, peeled, and sliced to a uniform size (22 ± 1 mm diameter and 3 ± 0.1 mm thick) using a circular cutting mold. The weight of each slice was 0.52 ± 0.03 g. Palm oil (Yihai Kerry Co., Ltd., Shanghai, China) was used as a frying oil. Vitamin E served as an antioxidant at the oil temperature was constant during frying, and the experiment and the ratio of samples to oil was maintained at about 1:50 (g/mL). After frying, the samples were removed from the fryer, and drained at room temperature for 10 min to remove excessive surface oil. Fig. 1 showed the experimental design which contained ultrasound pretreatment and frying procedure. Abbreviation of U0F0: control samples (without ultrasound pretreatment and frying). Abbreviation of U1F0 and U2F0: samples were treated inside the ultrasonic bath at the power of 360 and 600 W for 60 min (without frying). Abbreviation of U0F1: samples were fried at temperatures of 180 °C for 140 s (without ultrasound pretreatment). Abbreviation of U1F1 and U2F1: samples were treated inside the ultrasonic bath at the power of 360 and 600 W for 60 min, then they were fried at temperatures of 180 °C for 140 s. All potato chips exhibited low moisture content (below 2.5%) when the frying reached 140 s. All pretreatments and frying processes were performed in triplicate.

2.3. The extraction of potato starch

The starch of potato slices and the slices with ultrasound pretreatment was extracted by the method of Guo et al. [26] with minor modification. The ultrasound pretreatment slices were homogenized with deionized water using a homogenizer (Tianlin Instrument Co., Ltd., Jiangsu, China). Then homogenate was filtered through 100 mesh sieve and settled 12–16 h at 4 °C. The supernatant was removed and the sediment was washed using distilled water. Finally, the sediment was put into the heating oven (Binder, Germany), and then they were dried at 40 °C for 12 h to obtain potato starch for further analysis.

2.4. Water status analysis

The water status of potato slices was measured by LF-NMR according to Fan et al. [27] with little modifications. Approximately 10 g of potato slices were put into a 25 mm glass tube and inserted in an LF-NMR analyzer (MesoMR23 – 060 V – I, China). The magnet strength was 0.5 T, and the magnetic fields was 23.3 MHz at 32.00 °C. Transverse relaxation time (T2) and percentage of water fraction (A2) were analyzed using LF-NMR analyzer software (Carre – Purcell – Meiboome – Gill). The parameters of optimal pulse were as follows: SW = 200 KHz, SF = 21 MHz, RDF = 0.080 ms, RG1 = 10.0 db, P1 = 7.00 us, DGR1 = 3, TD = 320026, PRG = 2, TW = 4000 ms, P2 = 14.48 us, TE = 0.200 ms, NS = 8, NECH = 8000.

2.5. Measurement of starch properties

2.5.1. SEM observation of micromorphology

Changes in the starch granule morphology of untreated and ultrasound pretreated potato slices were investigated by a scanning electron microscope (SEM, Quanta 200, Fei Company, Holland). Starch samples were mounted on the specimen holder, then sputtered with a thin gold layer. The samples were observed in a relatively low acceleration voltage (3.0 kV), and the magnifications employed were 1.00 k × and 2.50 k ×.

2.5.2. Swelling power and solubility

Swelling power and solubility were measured as described by Cheng et al. [28] with small modifications. The suspensions (100 mL) of 2% potato starch were prepared in the beaker, and they were put in a 90 °C water bath for 30 min with continuous oscillation. After cooling to room temperature, the samples were collected by a centrifuge tube with a closed screw cap and centrifuged at 3000 r/min for15 min. The sediments were collected and weighed (W1), and the supernatants were weighted (W2), then dried at 105 °C until a constant weight (W3) reached. The Eqs. (1) and (2) were used to calculate the solubility (S) and the swelling power (SP):

\[ S(\%) = \frac{W_3}{W_2} \times 100\% \quad (1) \]

\[ SP (g/g) = \frac{W_1}{[W_2 \times (100-S)]} \quad (2) \]

where W was the weight of starch samples.
2.5.3. Thermal properties analysis

The thermal properties of starch samples were measured by a differential scanning calorimeter (DSC3, Mettler Toledo, Switzerland). Before the DSC determinations, the starch samples were ground into powder and sieved by a 100 mesh sieve. Various starch samples were weighted (approximately 4 mg) and transferred into an aluminum pan. Then 8 μL deionized water was added and the pans were sealed immediately. The sealed aluminum pans were kept at 24–25 °C for 12 h. All samples were heated from 30 °C to 90 °C with a rate of 10 °C/min, with an empty aluminum as reference. DSC3 analysis software was used to compute the onset temperatures (To), the peak temperatures (Tp), end set temperatures (Te), and gelatinization enthalpy (ΔH).

2.5.4. Crystalline structure analysis

Crystalline characteristics of starch samples were measured by an X-ray diffractometer (D2 PHASER, Bruker, Germany) at 40 kV and 30 mA Cu-Kα radiations. The X-ray diffraction grams were collected from 4° to 40° with a step size of 2 θ/min.

2.6. Examination of pore characteristics

Pore properties and pore size distribution of potato slices (U0F0, U1F0, and U2F0) and fried samples (U0F1, U1F1, and U2F1) were measured by MIP, and a mercury porosimeter (Poremaster GT-60, Quantachrome Instruments, U.S.A.) was used to determine the pore characteristics according to the methodology implemented by Zhang et al. [29] with small revision. Before analyzing pore characteristics, samples have to be dehydrated and deoiled. Samples were dehydrated using freeze-drying, and then deoiled using Soxhlet method. After draining oil and water, the samples (the weight about 5 g) were placed in the penetrometer. Firstly, the penetrometer assembly was loaded in the low-pressure port. Secondly, residual air of potato chips was evacuated and the initial mercury intrusion subsequently took place. Finally, the penetrometer was transferred into the high-pressure port. Pressure ranged from 0.006 MPa to 69.431 MPa. The generated data was output and performed with Porowin software.

2.7. Determination of oil content and oil fraction

Oil content and oil fraction were determined according to the method of Bouchon et al. [30] with a little modification. There are three oil fractions, including surface oil (SO), penetrated surface oil (PSO), and structure oil (STO). SO represents the oil that remains on the sample surface, while PSO represents the oil penetrates the samples during the cooling stage, and STO is the oil that was absorbed into the samples during frying. The total oil (TO) consists of the above three parts. The oil content was expressed in g/g dry basis (db) of potato chips.

Oil fractions (SO, PSO, and STO) were determined by dye oil methods. An aluminum box was prepared with 30 mL petroleum ether, and the potato chips were immersed in petroleum ether for 1 s at 20 °C. Then petroleum ether was volatilized and the oil in an aluminum box was dried at 105 °C until it reached a constant weight. This constant weight of oil was SO. After removing SO, soxhlet method was used to measure PSO and STO by SOX406 Fat Analyzer (Jinan Hanon Instruments Co., Ltd., Jinan, China). The Eqs. (3) and (4) were used to calculate the PSO and the STO:

\[ \text{PSO (g)} = \left( \frac{\text{Soxhlet extracted oil (g)} \times \text{Dye concentration in extracted oil (g/L)}}{\text{Dye concentration in frying oil (g/L)}} \right) \]  

\[ \text{STO (g)} = \text{Soxhlet extracted oil (g)} - \text{PSO (g)} \]

The TO (g) was the sum of SO and Soxhlet extracted oil. The oil content of different fractions was expressed in g/g dry basis of the potato chips.
2.8. Statistical analysis

All measurements were conducted in triplicates. SPSS 19.0 (SPSS v19.0, IBM, USA) and Origin 8.0 (Origin Lab Corporation, Northampton, England) were used for data analysis. Average values (AV) and standard deviations (SD) were determined and expressed as AV ± SD. Analysis of variance (ANOVA) was used to examine the difference between the mean values at the 95% confidence level (p < 0.05).

3. Results and discussions

3.1. Water status of ultrasound pretreated slices

Distribution of transverse relaxation times (T2) in control samples (U0F0) and ultrasound pretreated samples (U1F0 and U2F0) was measured by LF-NMR. Water status constitute three types, which related to the binding energy and mobility of water, including bound water, immobilized water, and free water. The short T2 times represented a tighter linkage between moisture molecular and sample structure [16]. Three peaks were observed in each sample from left to right (Fig. 2), including T21 (1–8 ms), T22 (10–80 ms), and T23 (100–800 ms). Additionally, the T2 time was associated with water status. The T21, T22, and T23 represented bound water, immobilized water, and free water, respectively [27]. Three peaks could be found in the T2 curves of U0F0, U1F0, and U2F0 potato slices; moreover, the area of each peak represented the quantitative changes of three states of water.

The transverse relation time values (T21, T22 and T23) and percentage of water fraction (A21, A22, and A23 values) of three samples were shown in Table 1. T21 values of the U0F0, U1F0 and U2F0 potato slices did not show significant differences (p < 0.05). Compared to the control samples, A21 values showed a significantly increase trend in U1F0 and U2F0 potato slices samples, and the value of U1F0 was higher than that of U2F0. The result indicated that ultrasound pretreatment led to an increase in the fraction of bound water. The cause might be that the transient and repetitive cavitation caused the formation of radicals (H radicals and OH radicals) in water media, and cavitation simultaneously can lead to the damage of samples microstructure when attacked by ultrasound waves [31]. Therefore, these were in favor of the combination of radicals and the generation of molecular products, which was the main cause of the increase in bound water. It is obvious that the T22 values of pretreated samples were lower than that in control samples; moreover, the values decreased with the increase in ultrasound power. The A22 values of potato slices increased after sonication. Additionally, the increase in ultrasonic power led to the reduction in A22 values. The results pointed out that immobilized water content increased after being treated with ultrasonic. The immobilized water fraction of U0F1 samples was higher than that of U2F0 samples. The fraction of immobilized water might be related to the integrity and rigidity of cell walls. Distilled water was used as an ultrasound medium to pretreat potato slices and water filled the cell interstitial, which resulted in the structure becoming rigid of U0F1 and U0F2 slices samples. While the increase in ultrasonic power might lead to the disruption of cellular and the change of cell membrane permeability [32]. This was perhaps the principal reason for the decrease in the immobilized water fraction of U0F2 samples compared with U0F1 samples. No significant differences in T23 and A23 values were observed between ultrasound treated potato slices (U1F0 and U2F0) and control slices (U0F0), indicating ultrasound pretreatment did not affect the fraction of free water.

3.2. Starch properties of ultrasound pretreated slices

3.2.1. Morphological observation (SEM)

SEM was used to understand the effect of ultrasound pretreatment on morphological changes of potato starch. As shown in Fig. 3, all samples exhibited a typical spherical and ellipsoid shape, corroborating the shape of potato starch granules reported by Dhital et al. [33]. Interestingly, some bulges were observed on the surfaces of all starch samples, which was probably related to the biochemical processes of building starch granules by transforming photosynthesis into glucose [34]. It was observed that U0F0 starch granules had smooth surfaces and flat edges (Fig. 3a). Fig. 3b and c presented the influence of
ultrasounds on morphological of starch samples. It exhibited the integrity and the size of U1F0 and U2F0 samples did not change. However, the notches and grooves were observed in the surface of starch granules (U1F0 and U2F0), and the damages were aggravated with increasing sonication power. The slight scratches were observed on the surface of U1F0 starch samples, and obvious erosion was presented on the surface of U2F0. It was apparent that ultrasound pretreatment caused a little bits or grains to gradually break away from the outer layer of starch. Similar results were reported by Cui et al. [35].

The noticeable changes on the surface of ultrasound pretreated starch samples for the following reasons. Ultrasound irradiation extensively attacked the starch granules, including high pressure, shear forces, shock waves, and water impinging. This was attributed to the formation of fast cavitation bubbles, the strong collision of cavitation bubbles, and the fast collapse of cavitation bubbles [36]. Moreover, the free radicals (OH radical and H radical) content increased in ultrasound medium (water), which was induced by the aggressive behavior of ultrasound irradiation when the potato samples were subjected to the action of ultrasonic [35]. These radicals might promote the degradation of the cluster and the disruption of internal structure, which had a negative impact on the smooth surfaces and flat edges of starch samples.

### 3.2.2. Swelling power and solubility

The variation of swelling power and solubility of potato starch affected by ultrasound pretreatment was presented in Table 2. The swelling power and solubility of potato starch without pretreatment were 0.11 g/g and 6.94%, respectively. The swelling power of U1F0 was 3.85% lower than that of U0F0, and the solubility decreased by 14.72% compared with U0F0. However, there was no significant difference in swelling power and solubility between the U0F0 and U2F0 (p < 0.05). Ultrasonic waves induced gas bubbles or cavities within the potato matrix, which was called the cavitation process. Stable cavitation occurred, and a current of microbubbles generated with lower power ultrasonic. Those microbubbles can result in microstreaming in the ambient fluid, which induced stress in potato tissue [31]. Accordingly, ultrasound pretreatment with lower power might lead to a densification of the potato internal structure. When the ultrasound power increased, transient cavitation occurred, and the microbubbles began to be unstable in size. When the microbubbles reached the critical size, microbubbles collapsed. The explosive disruption of bubbles caused the generation of heat production, local pressure, and shear forces, which resulted in structural damages [37].

The swelling power and solubility represented the hydration of starch, which is related to the intermolecular forces of starch [29]. For the U1F0 potato samples, densification played a primary role in the structure of starch rather than disruption. It might affect the polar groups of starch, which reduced the ability of water molecules binding

| Samples   | T21 (ms) | T22 (ms) | T23 (ms) | A21 (%) | A22 (%) | A23 (%) |
|-----------|----------|----------|----------|---------|---------|---------|
| U0F0      | 4.59 ± 2.18a | 28.75 ± 1.63a | 403.70 ± 0.64a | 0.29 ± 0.03a | 2.83 ± 0.46a | 95.15 ± 0.38a |
| U1F0      | 4.14 ± 1.14a | 24.93 ± 2.49b | 403.70 ± 0.33a | 1.76 ± 0.47b | 4.12 ± 0.04b | 95.26 ± 0.63a |
| U2F0      | 5.38 ± 1.06a | 27.14 ± 1.92ab | 403.70 ± 1.03a | 0.90 ± 0.09c | 3.34 ± 0.06c | 95.76 ± 0.33a |

Different lowercase letters indicate significant differences (p < 0.05) of the values in the same column.

| Samples | Swelling power (g/g) | Solubility (%) |
|---------|----------------------|----------------|
| U0F0    | 0.11 ± 0.005a        | 6.94 ± 0.07a   |
| U1F0    | 0.10 ± 0.001b        | 5.92 ± 0.05b   |
| U2F0    | 0.11 ± 0.002ab       | 6.88 ± 0.02b   |

Different lowercase letters indicate significant differences (p < 0.05) of the values in the same column.

The SEM images of starch samples (a1 – 2), (b1 – 2), and (c1 – 2) are shown in Fig. 3. The magnifications of images from top to bottom in the same line were 1 and 2.5 K, respectively.
to the amylose and amylopectin. Thus the decrease in swelling power and solubility of U1F0 samples was related to the decrease in the exposure of polar groups of starch. Nevertheless, damage to construction induced by higher power ultrasonic was more serious than the densification of U2F0 potato samples, and it increased the dissolution of amylose and amylopectin. This might be the main cause of higher swelling power and solubility values of U2F0 samples compared with U1F0.

3.2.3. Thermal properties

In order to verify the changes in the thermodynamic properties of ultrasound pretreatment samples, DSC determinations were exhibited in U0F0, U1F0, and U2F0 potato samples. As presented in Table 3, compared with U0F0 samples, it showed that no significant changes were displayed in the gelatinization temperatures (To, Tp, and Te) of U1F0 and U2F0 samples. However, a decrease in enthalpy (ΔH) was found for U2F0 samples, which indicated that it required less energy for gelatinization compared to U0F0 and U1F0 starch samples. The ΔH values of starch were positively correlated to the chain length of amylopectin due to the higher energy requirement for gelatinization of long chain length [36]. In addition, the destruction of double helices chains was reflected by the ΔH values, and the loss of double helices indicated the less energy requirement for gelatinization [38]. Therefore, the decrease in ΔH of U2F0 might be attributed to the following factors: (1) the ultrasound pretreatment with high power produced the reversible hydration of the amorphous phases and disturbed the starch structure; (2) the ultrasound pretreatment of U2F0 starch samples disrupted the hydrogen bonds; (3) the disruption of the potato internal structure caused by ultrasound pretreatment resulted in a less energy requirement for gelatinization of U2F0 samples. The result was consistent with the studies by Monroy et al. [39] and Yang et al. [40].

3.2.4. X-ray diffraction (XRD)

The X-ray diffraction patterns of control samples (U0F0) and ultrasound pretreated samples (U1F0 and U2F0) were shown in Fig. 4. The diffraction peaks of U0F0 starch samples were presented at about 5.5° and 17°, and an unresolved shoulder peak around 22° and 24°. This result indicated that its crystalline pattern was a typical B-type, which was consistent with the results of previous researches [28]. The diffraction intensities and diffraction patterns of U1F0 and U2F0 samples were similar to those of U0F0 samples, which indicated that the ultrasound pretreatment had not change the crystal morphology of these starch samples. Zhu et al. [41] and Yang et al. [40] also observed that ultrasound exerted barely affected the diffraction intensities and diffraction patterns in XRD patterns of starch.

3.3. Pore characteristics

MIP was allowed to define porosity, bulk density, pore volume, and pore size distribution of potato slices. With MIP, pores between about 0.02 μm and 250 μm in diameters can be investigated [42]. As represented in Fig. 5(a), there was an obvious influence of ultrasound pretreatment on the pore parameters and pore size distribution of potato slices. It was clearly shown that the porosity and bulk density increased, while the total pore volume decreased with the pretreated of ultrasound. That might be related to the variation of potato structure and the absorption of water during ultrasound pretreatment [17]. The increase in bulk density illustrated an increase in mass per unit volume of potato chips due to ultrasound pretreatment. The densification of the structure of samples corresponded with the illustration in the previous Section 3.2.2, thus the increase in bulk density and decrease in total pore volume were strongly fitted with the swelling power and solubility data of ultrasound pretreated samples depicted by Table 2. As seen from the pore size distribution curves (Fig. 5a), the mean pore size diameters ranged from approximately 11 μm to 300 μm of three potato slices samples. When slices samples were treated with ultrasound, a small contribution of pores (diameters with 7–12 μm) were observed in U1F0 and U2F0 samples. Additionally, as ultrasound power increased, there was a slight increase in pores with diameters of 0.4–3 μm, but pores with diameters of 11–300 μm decreased (U2F0). Ultrasound pretreatment caused the formation of pores with a smaller size. This was an expected result since ultrasound could create microchannels, which were produced by the rapid alternating contraction and expansion of ultrasound waves. This was also in concert with the variation of the starch microstructure as discussed previously.

Fig. 5(b) showed the pore size distribution and pore properties of U0F1, U1F1, and U2F1 fried samples. Compared with U0F1, the porosity, bulk density, and total pore volume of potato chips with ultrasound pretreatment (U1F1 and U2F1) were reduced. Pores in three fried samples were mainly in the range of diameters 3–250 μm. As ultrasound power increased, the volume proportion of the diameters of pores of 30–200 μm showed a decreasing trend in fried potatoes, meantime, the proportion of pores with diameters 3–30 μm increased. Generally, the ultrasound pretreatment before frying resulted in a decreasing trend in the amount of smaller size pores of potato chips and a shift of the pore volume to a smaller size. In the process of frying, the water turned into vapors and migrated from the center to the outside layer of the samples at high temperatures, causing the change in microstructure and the formation of the microchannels during frying [22,43,44]. Thus, ultrasound treatment prior to the frying process resulted in the variation of pore characteristics of potato chips, which was related to the changes of

![Fig. 4. X-ray diffraction patterns of U0F0, U1F0, and U2F0 starch samples.](image-url)
Fig. 6 depicted the TO content and various oil fractions (SO, STO, and PSO) content of potato chips under different ultrasound pretreatment conditions. The effect of ultrasound pretreatment on oil absorption was also illustrated. The content of SO, PSO, STO, and TO of fried samples significantly changed (p < 0.05). The SO content exhibited an increase after ultrasound pretreatment. It might be related to the surface roughness of samples. More oil remained at the samples surfaces, which was attributed to the fact that the pretreated samples developed rougher surfaces after ultrasound treatment. The PSO content of U1F1 fried samples reduced by 27.31%, while it was observed that PSO content of U2F2 fried samples increased by 12.89%. Compared with the samples without ultrasound pretreatment (U0F1), the STO content of U1F1 and U2F2 fried samples reduced by 22.25% and 38.05%, respectively. The U0F1 fried samples presented the highest TO content in all samples. Compared with U0F1 samples, higher TO content reduction (23.92%) of U1F1 fried samples was presented, whereas the TO content of U2F1 fried samples was 13.37% less than that of U0F1 samples. Therefore, the decrease in PSO and STO content together contributed to the reduction in the TO content of U1F1 samples, while the reduction of STO content was the main factor that led to the TO content decrease of U2F1 samples. Oladejo et al. showed that using ultrasonic before frying at 150 °C and 170 °C had 65.11% and 71.47% oil reduction of sweet potatoes during deep-fat frying, respectively, compared with untreated sweet potatoes [16]. Similarly, Jalal et al. pretreated potato strips with ultrasonic at 28 and 40 kHz before frying, and they reported that oil absorption of samples pretreated with ultrasonic significantly decreased (P < 0.05) [45]. However, another study showed that ultrasound pretreatment had no significant effect on oil uptake of potato strips [46]. This might be related to the difference in the application of ultrasound power or frequency prior to frying.

The changes of PSO fraction were related to the cooling phase effect mechanism of oil uptake. As a surface phenomenon, the oil uptake was mainly related to the drainage of oil from the surface and the suction of oil with the matrix. More oil migrated into the inner of fried samples when fried samples were removed from the frying medium, which might be due to the high native pressure in the interior induced by the high different temperature between the inner core and the surface [47]. The potato slices were immersed in distilled water and pretreated by ultrasound with lower power. This might lead to a densification of the potato internal structure, which hindered the infiltration of oil into the interior. Hence, the PSO content of U1F1 samples was reduced. With the increase in ultrasonic power, the structure of samples was damage more seriously. The severe destruction of the surface structure observed by SEM can stimulate PSO fraction absorption. The formation of

**Fig. 5.** Pore size distribution curves and pore parameters of ultrasound pretreated potato slices (a) samples and fried samples (b).
microscopic channels might play an important role in the increase in oil infiltration of U1F2 fried samples. Moreover, the erosion and formation of notches depicted by Fig. 3 strongly fitted with the PSO content of U0F1 and U2F0 samples. The reduction of STO content was related to the moisture replacement mechanism of oil uptake. Moisture turned into vapors and tended to leave the structure of potato samples. The formation of pore spaces due to the dehydration of the potato matrix was responsible for oil absorption during the frying process [48]. Ultrasonic waves caused a serious alternate expansion and compression effect. The formation of porous structure resulted in a decrease in the diffusion boundary layer and the increase in convective mass transfer [49]. The cracks and cavities appeared at the surface, which also improved water diffusion by providing more channels. Thus ultrasound pretreatment was in favor of the moisture loss. The enhancement of mass transfer can create high vapor pressure within the inner core of samples, which could remove strongly attached water easier. The reduction of STO content was related to the higher vapor pressure inside the matrix, and which led to a meaningful reduction in oil penetration into the potato tissue during frying. Similar results were presented by Oladejo et al. [16] and Samira et al. [17]. Generally, the application of ultrasound pretreatment produced an effect on water state, starch granule morphology, and pore size of potato slices. All these changes could in turn cause the changes in the oil content and oil fraction of potato chips (Fig. 7).

4. Conclusions

In this study, the changes in the properties of potato starch were studied after ultrasonic. SEM images showed that ultrasound pretreatment induced an increase in the surface roughness of potato starch by forming notches and grooves, but potato starch granules can maintain the characteristic shape and integrity. Low power ultrasound pretreatment led to a decrease in swelling power and solubility, which did not change after high power ultrasound pretreatment. High power ultrasound treated decreased the AHW. The immobilized water fraction and bound water fraction of potato slices increased after sonication. Ultrasound pretreatment caused the formation of pores with diameters 11–300 μm; moreover, pores with diameters of 0.4–3 μm were observed at high ultrasound power. The results showed that the potato slices pretreated with ultrasound at 360 W (60 min) and 600 W (60 min) had less oil absorption compared with control potato slices. The PSO content and STO content were reduced at the low ultrasound power (360 W), while the STO content reduced, and the SO content and STO content increased at the high ultrasound power (600 W).

CRediT authorship contribution statement

Jin Zhang: Methodology, Data curation, Writing - original draft. Peibin Yu: Methodology, Data curation. Liuping Fan: Conceptualization, Supervision, Validation, Writing - review & editing. Yong Sun: Methodology, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] W.A.M. Van Loon, et al., Identification and olfactometry of French fries flavour extracted at mouth conditions, Food Chem. 90 (3) (2005) 417–425.
[2] I.S. Saguy, D. Dana, Integrated approach to deep fat frying: engineering, nutrition, health and consumer aspects, J. Food Eng. 56 (2) (2003) 149–152.
[3] C. Sayon-Orea, et al., Consumption of fried foods and risk of metabolic syndrome: the SUN cohort study, Clin. Nutr. 33 (3) (2014) 545–549.
[4] V.M. Kartzaki, et al., Effect of ultrasound-assisted osmotic dehydration as a pretreatment on deep fat frying of potatoes, Food Bioprocess Technol. 6 (12) (2013) 3554–3563.
[5] R. Foster, C.S. Williamson, J. Lunn, BRIEFING PAPER: culinary oils and their health effects, Nutr. Bull. 34 (1) (2009) 4–47.
[6] M. Kurek, M. Ščetar, K. Galic, Edible coatings minimize fat uptake in deep fat fried products: a review, Food Hydrocolloids 71 (2017) 225–235.
[7] L. Yu, et al., Effect of guar gum with glycerol coating on the properties and oil absorption of fried potato chips, Food Hydrocolloids 54 (2016) 211–219.
[8] Y. Zhu, B. Bhandari, S. Prakash, Tribo-rheology characteristics and microstructure of a protein solution with varying casein to whey protein ratios and addition of hydrocolloids, Food Hydrocolloids 89 (2019) 874–884.
[9] E. Mah, J. Price, R.G. Brannan, Reduction of oil absorption in deep-fried, battered, and breaded chicken patties using whey protein isolate as a postbreading dip: effect
