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Potato Slices Drying: Pretreatment Affects the Three-Dimensional Appearance and Quality Attributes

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Abstract: In the current study, the effects of steam blanching, saline immersion, and ultrasound pretreatment on the drying time, three-dimensional (3D) appearance, quality characteristics, and microstructure of potato slices were investigated. All the pretreatment methods enhanced the drying kinetics relative to the untreated potato slices. The 3D appearance was evaluated by reconstructed 3D images, shrinkage, and curling degree. The reconstructed images could well reproduce the appearance changes in the potato slices during drying. All the three pretreatment methods reduced the shrinkage during the drying process relative to the untreated potatoes. The curling degree was evaluated by the height standard deviation (HSD) of the material surface. The results showed that saline immersion inhibited the curling of the potato slices during the drying process, while ultrasound aggravated the curling of the potato slices. The potatoes treated by blanching obtained a lower total color difference (ΔE), higher total polyphenol content, and antioxidant capacity compared with the samples treated with saline immersion and ultrasound pretreatments. The observation of the microstructure by scanning electron microscope (SEM) verified the effects of the pretreatments on the drying time and appearance deformation. Therefore, it is of great significance to regulate the 3D appearance and quality characteristics of agricultural products during the drying process by an appropriate pretreatment.

Keywords: potato; pretreatment; drying; three-dimensional appearance; quality; microstructure

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1. Introduction

Potato (*Solanum tuberosum* L.) is known as one of the world's five major crops along with corn, rice, wheat, and sorghum [1]. Potato is rich in nutrition, including starch, protein, vitamins, polyphenols, and trace elements, so it is used as a favorite composition of functional food [2,3]. Therefore, potato is getting higher and higher in the position of agricultural and sideline products, and the demand is also growing. However, potato, like other vegetables, has a high moisture content, so it is easy for it to rot and sprout during storage [4]. This has a great effect on the quality of potatoes [5]. Drying is an effective way to prolong the shelf life of fruits and vegetables.

There are many drying methods used in the processing of fruits and vegetables, including hot-air drying, infrared drying, freeze drying, microwave drying, and hybrid drying technology [6,7]. Each drying technique has its own advantages and disadvantages. However, the most commonly used drying method in potatoes is still hot-air drying [8]. Drying can effectively prevent the growth of microorganisms, reduce enzyme activity, and slow down some water-mediated chemical reactions [9,10]. However, the drying process always consumes a lot of energy and will have a significant impact on the shape, color, flavor, and nutrition of dried products [10]. Therefore, it is necessary to develop operations to minimize the adverse effects of the drying process, reduce the time and energy requirements, and maximize the retention of the original characteristics of the product [11].

Fruits and vegetables are usually subjected to physical or chemical pretreatment before drying to shorten the drying time, reduce the energy consumption, and preserve the quality of products [12]. It was found that blanching pretreatment can damage the structure of cell membranes and thus shorten the drying time [13]. Mehta et al. [14] reported that dried vegetables coupled with blanching as a pretreatment showed less degradation in terms of polyphenols and flavonoids. Liu et al. [15] observed that blanching pretreatment could not only shorten the drying time but also inhibit browning and maintain the anthocyanin level in purple-flesh sweet potato drying. It has also been reported that vacuum-dried potato chips pretreated with blanching have a better texture and a lower glycemic index [16]. Osmotic solution immersion pretreatment, such as sucrose or salt solution, has been widely used in drying pretreatments because of its ability to ensure the quality of dried products [17]. Zou et al. [18] reported that sucrose solution immersion pretreatment can improve the color and sensory quality of dried products. It was reported that osmotic solution pretreatment shortens the drying time and reduces the specific energy consumption in potato drying [19]. Moreover, Chinenye et al. [20] found that the volume of potato chips treated by saline immersion was higher by 6% than non-treated samples.

Ultrasound as a pretreatment method has attracted considerable interest in drying processes, since it can form microscopic channels in the tissue due to cavitation and sponge effects, which can promote the migration of water and accelerate the drying process [21,22]. For potato slices drying processes, it has been reported that ultrasound pretreatment can effectively shorten the drying time and reduce the specific energy consumption [23]. Zhang et al. found that ultrasound pretreatment can increased hardness of potato chips and reduce the destruction of the cellular structure [24]. The results of Xu et al. [25] showed that ultrasound pretreatment could improve the content of flavonoids and polyphenols in dried products. Rashid et al. [26] also reported that appropriate ultrasound pretreatment can well maintain phytochemical compounds. Generally speaking, suitable pretreatment before a drying process can improve the drying efficiency and enhance the product quality, but few people have paid attention to the influence of pretreatment on the appearance changes in dried products.

Appearance (especially for 3D appearance) is one of the most important indicators for people when evaluating dried products, and it has a great impact on subsequent further processing, packaging, and transportation [27]. For consumers, products with a uniform and regular appearance generally have a better degree of acceptability. At present, the main method for studying the appearance changes in dried samples is through two-dimensional images. For example, Khazaei et al. [28] applied an analog camera collect images to monitor shrinkage during dehydration in grape drying. However, a single camera can only obtain the data of a projected area of a sample's surface, and the thickness change in the material cannot be measured effectively. Therefore, Sampson et al. [29] used top and side cameras to obtain the thickness and projected area of materials so as to measure the volume changes in apple slices during the drying process. However, a side camera cannot fully reflect the thickness change during the drying process of the material. In addition, a two-dimensional image cannot perfectly simulate the morphological change in the drying process that occurs in a 3D space. Therefore, it is necessary to use 3D image technology to evaluate the shape change in materials during drying. Cai et al. [30] used a Kinect V2 sensor to build an image acquisition platform, and the morphological changes in potato slices under different drying temperatures were studied. However, the detection accuracy of a Kinect sensor is relatively low [31], which makes the quantification and analysis of 3D information rough. Therefore, there has been less information about the 3D appearance changes in fruits and vegetables during drying by pretreatment methods.

The objective of this study was to investigate the effects of blanching, saline immersion, and ultrasound pretreatments on the drying time, internal quality, and external quality characteristics of dried potato slices, including the 3D appearance, color, total polyphenol content, antioxidant properties, and microstructure.

2. Materials and Methods

2.1. Material

Fresh potatoes of the same variety "Holland fifteen" were purchased from a supermarket near Jiangsu University (Zhenjiang, China). All the potato samples were transported to the laboratory and stored at room temperature (about 20 °C) before experimentation. The average initial moisture content of potatoes was 84.23 ± 2.36% (wet basis). Before drying, the potatoes were washed, peeled, and sliced to a thickness of 2 mm using an electric slicer (MS-305C, Foshan Komle Electric Appliance Co., Ltd., Foshan, China). Then, the samples were subjected to pretreatment.

2.2. Pretreatment Methods

In this study, potato slices were subjected to three kinds of pretreatments. (1) For steam-blanching pretreatment, potato slices were processed by steam cooker (total volume 4 L) at atmospheric pressure. The power of the steam cooker was 1000 W to ensure the continuous boiling of the water. The blanching times were 30, 60, and 90 s, respectively. (2) Saline immersion pretreatment was referred to as the method of Chinenye et al. [20] with some modifications. Potato slices were soaked in a salt solution for 60 min. The concentrations of the salt solutions were 5%, 10%, and 20%, respectively. (3) For ultrasound pretreatment, the potato slices were immersed in distilled water and then subjected to an ultrasound bath. The parameters set to 240 W and 40 °C according to the relevant studies. The treatment times were 10 min, 30 min, and 60 min, respectively.

2.3. Hot-Air Drying Experiment

The potato slice samples were dried in hot-air drier, which was described in previous study [30]. The drying process was carried out at 65 °C with an air velocity of 3 m/s and a relative humidity of 10% (RH). A quantity of 100 ± 5 g samples was used for all drying runs in the experiment. The weight loss was periodically recorded by taking out the rotating glass and weighing it on an electronic balance within an accuracy of ±0.01 g during drying. Drying was stopped when the moisture content of the samples reached the desired final moisture content of 6.00% (wet basis). All the drying experiments were conducted in triplicate.

2.4. Moisture Ratio (MR)

The moisture ratio was calculated using Equations (1) and (2).

$$\mathrm{MR} = \frac{\mathrm{M_t} - \mathrm{M_e}}{\mathrm{M_0} - \mathrm{M_e}} \tag{1}$$

where $\mathrm{M_0}$ is the initial dry basis moisture content; $\mathrm{M_t}$ is the dry basis moisture content at the drying time t; MR is the moisture ratio; and $\mathrm{M_e}$ is the equilibrium moisture content. The equilibrium moisture content, $\mathrm{M_e}$, was much smaller than $\mathrm{M_0}$ and $\mathrm{M_t}$ and could generally be ignored [32]. Therefore, the calculation of MR can be simplified as:

$$\mathrm{MR} = \frac{\mathrm{M_t}}{\mathrm{M_0}} \tag{2}$$

2.5. Three-Dimensional Appearance Evaluation Index

The 3D image acquisition platform used in this experiment was independently built by the team [33]. Using binocular snapshot sensor (Gocator3210, LMI technologies Inc., Vancouver, BC, Canada), the measurement range was −50~50 mm in the horizontal direction, −77~77 mm in the vertical direction, −55~55 mm in the depth direction, and the detection accuracy was ±0.035 mm. The 3D point cloud images were periodically collected at an interval of 10 min during drying. The collected images were processed by the software Cloud Compare (version 2.1), including background removal, noise removal, point cloud filtering, and surface reconstruction.

The time-varying appearance images of one potato slice during drying is shown in Figure 1. The three images from top to bottom in each column represent a color physical image, 3D reconstructed image and height distributed image, respectively. The 3D reconstructed image obtained from the point cloud data was fairly close to the physical image of the potato slice, which benefitted from good measurement accuracy due to laser scanning [34,35]. Therefore, the reconstructed 3D images could well reproduce the appearance changes in the potato slices during drying. The height distribution of the potato slice in Figure 1 is represented by pseudo-color images, and the color from blue to red indicates that the height value of the pixels on the material changed from small to large. It was found that potato slice obviously curled with the process of drying, especially after a drying time of 40 min.

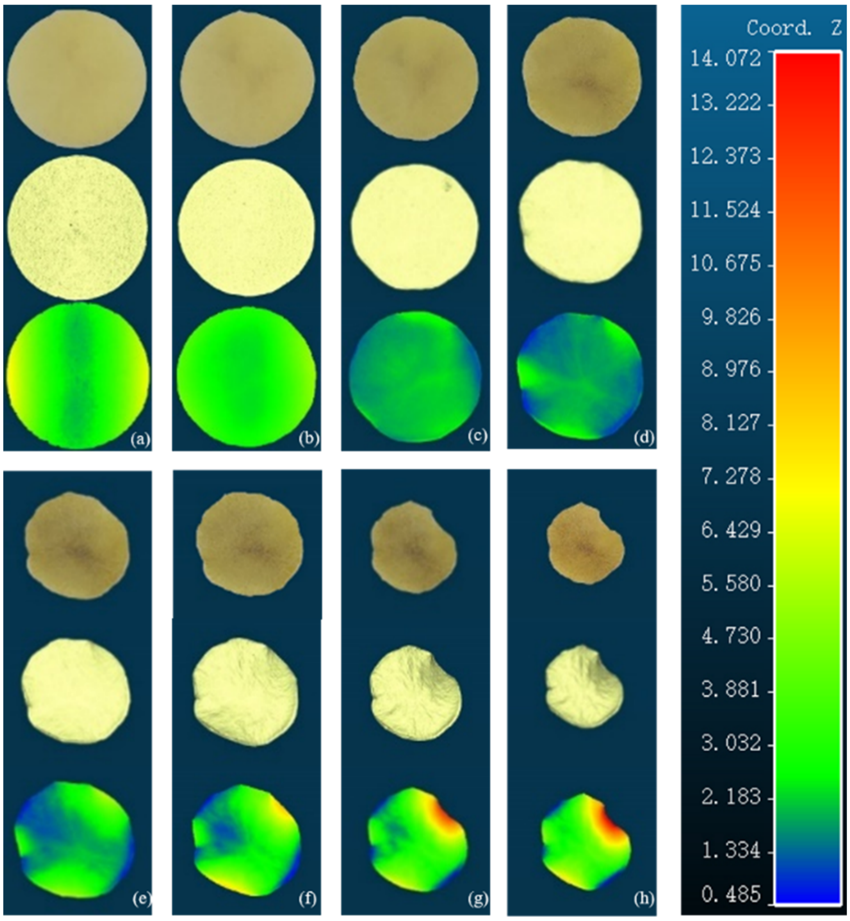

Figure 1. Time-varying appearance images of one potato slice during drying. (**a**–**h**) represent potato slices dried at 65 °C, 10% RH, 3 m/s for 0, 10, 20, 30, 40, 50, 60, and 70 min, respectively. The three images from top to bottom in each column represent color physical image, 3D reconstructed image, and height distributed image, respectively.

2.5.1. Shrinkage

The surface model was composed of tens of thousands of triangles. First, the distance between two points was calculated by Euclid's formula, and the three side lengths of each triangle could be obtained. For example, the distance between points p_1 (x_1, y_1, z_1) and p_2 (x_2, y_2, z_2) can be calculated by Equation (3). Then, the area of each triangle was calculated through Helen's formula, as in Equation (4), and the sum of the area of all triangles was calculated, which was the surface area. The shrinkage of the potato slices during drying could be calculated by the change in the surface area at different drying time points (Equation (5)). The specific equations are as follows:

$$d_{p_1p_2} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{3}$$

$$S_{ABC} = \sqrt{p(p - d_{AB})(p - d_{AC})(p - d_{BC})} \tag{4}$$

$$\text{Shrinkage} = \frac{S_0 - S_t}{S_0} \tag{5}$$

where $d_{p_1p_2}$ is the distance between the two points of p_1 and p_2; S_{ABC} is the area of the triangle ABC; and p is half of the circumference of the triangle ABC. S_0 is the surface area of the sample before drying, and S_t is the surface area of the sample during drying.

2.5.2. Height Standard Deviation

The appearance of the material changed from flat to curled during drying, which caused a change in the surface height value. The HSD could reflect the degree of dispersion of the surface height among individuals in a group. Therefore, the HSD was used to characterize the degree of curling of the material. The larger the value, the more uneven the surface of the material and the more severe the curling. The height value of the processed point cloud was extracted by the software, and the standard deviation of the height was calculated by Equation (6).

$$\text{Height standard deviation} = \sqrt{\frac{\sum_{i=1}^{n}(h_i - h_{av})^2}{n - 1}} \tag{6}$$

Among them, n is the number of point clouds; h_i is the height of the i-th point, mm; and h_{av} is the average height of n points, mm.

2.6. Color Measurement

The color of fresh and dried potato slices was determined using colorimeter (SC-10; Shenzhen 3nh technology Co., Ltd., Shenzhen, China). The color was represented by coordinates L^* (lightness), a^* (redness/greenness), and b^* (yellowness/blueness). For each condition, the collection of color parameters was repeated 9 times and averaged. In addition, the total color difference (ΔE) was calculated by Equation (7).

$$\Delta E = \sqrt{(L_0{}^* - L^*)^2 + (a_0{}^* - a^*)^2 + (b_0{}^* - b^*)^2} \tag{7}$$

where, $L_0{}^*$, $a_0{}^*$, and $b_0{}^*$ are the color parameters of the untreated dried potato slices, and L^*, a^*, and b^* are the color parameters of the pretreated dried potato slices.

2.7. Determination of Total Polyphenol Content (TPC)

Polyphenol extract was prepared by the following method: A total of 1 g of potato slice powder was extracted with 70% ethanol solvent. The potato powder and 50 mL solvent were mixed evenly at room temperature and then treated by ultrasound for 1 h at 40 °C, followed by centrifugation at 4000 rpm for 20 min to obtain the supernatant. The supernatant was the final polyphenol extract, and it was stored at 4 °C for further analysis.

The total polyphenol content (TPC) of the potato slices was determined by an improved Folin–Ciocalteu method [36]. Five hundred microliters of polyphenol extract were mixed with 1 mL Folin–Ciocalteu's reagent. After 2 min incubation at room temperature, 2 mL Na_2CO_3 (7.5%, *w*/*v*) was added and then fixed to 10 mL with distilled water. The resulting mixture was incubated for 60 min at room temperature. At the end of the incubation, the absorbance was measured at 775 nm using a UV–Vis spectrophotometer (754, Shanghai Jinghua Technology Instrument Co., Ltd., Shanghai, China). The results of the TPC were expressed as mg gallic acid equivalents (GAE) per gram of dried potato slices.

2.8. Determination of DPPH Radical Scavenging Assay

The DPPH radical scavenging assay was analyzed according to the method of Zhu et al. [37] and modified appropriately. DPPH solution (2 mL) solution was mixed with a certain volume of sample polyphenol extracts and then fixed to 5 mL with 70% ethanol solution. The reaction mixture was shaken well by a vortex blender (VORTEX-2, Shanghai Hutong Industrial Co., Ltd., Shanghai, China) and left standing for 30 min in a dark environment at room temperature. In the control group, 70% ethanol solution was used to replace the extract, and the preparation method was similar to that of the experimental group. The absorbance of the experimental group and the control group at 517 nm was measured by UV–Vis spectrophotometer (754, Shanghai Jinghua Technology Instrument Co., Ltd., Shanghai, China). The results were presented as percentage of DPPH radical scavenging activity utilizing the Equation (8).

$$\text{DPPH scavenging activity } (\%) = \frac{A_0 - A}{A_0} \times 100\% \tag{8}$$

where A_0 is the absorbance of the control group, and A is the absorbance of the sample group.

2.9. Microstructure

Microstructure images of the dried potato slices were obtained using a scanning electron microscope (SEM) (S-3400 N, Hitachi Ltd., Tokyo, Japan) according to the method described by Chu et al. [38]. Dried potato slices were cut into 5 mm × 5 mm with a blade and coated with gold in an ion sputter. The samples were observed in the high vacuum mode at an accelerating voltage of 15.0 kV. Samples were observed at a magnification of 100× and 500×.

2.10. Statistical Analysis

All statistical analyses were performed using three sets of parallel experimental data, and the experimental results were expressed as mean ± SD. Statistical analysis was performed using SPSS software (version 25.0, SPSS Inc., Chicago, IL, USA). The one-way analysis of variance and Duncan's test ($p < 0.05$) were used to determine whether there were significant differences between the groups.

3. Results and Discussion

3.1. Moisture Ratio (MR)

Figure 2 shows the MR curves and drying time of the potato slices under different pretreatments during hot-air drying. Compared with the untreated potato samples, blanching, saline immersion, and ultrasound pretreatment had obvious effects on the drying curves and drying time. The drying curve of the potato slices under different blanching times is shown in Figure 2I. The drying time was decreased by about 14.29% when the blanching time increased to 90 s. This phenomenon may be due to the fact that blanching can expel the intercellular air retention in sample tissues and weaken the resistance of cell membranes and cell walls to water diffusion through structure softening [39]. Similar results were found in studies on the drying process of apricots [40] and carrots [41].

For the saline immersion pretreatment in Figure 2II, when the salt solution concentration increased to 20%, the drying time of the potato slices decreased by about 35.71% compared with the untreated samples. The reason for this result may be that saline immersion can remove part of the free water in the material [18], which obviously led to a reduction in the drying time. In addition, it was reported that accumulation of solute (sucrose or salt) occurred in the space between the wall and plasmalemma, which plasmolyzed the cytoplasm and the vacuoles [42].

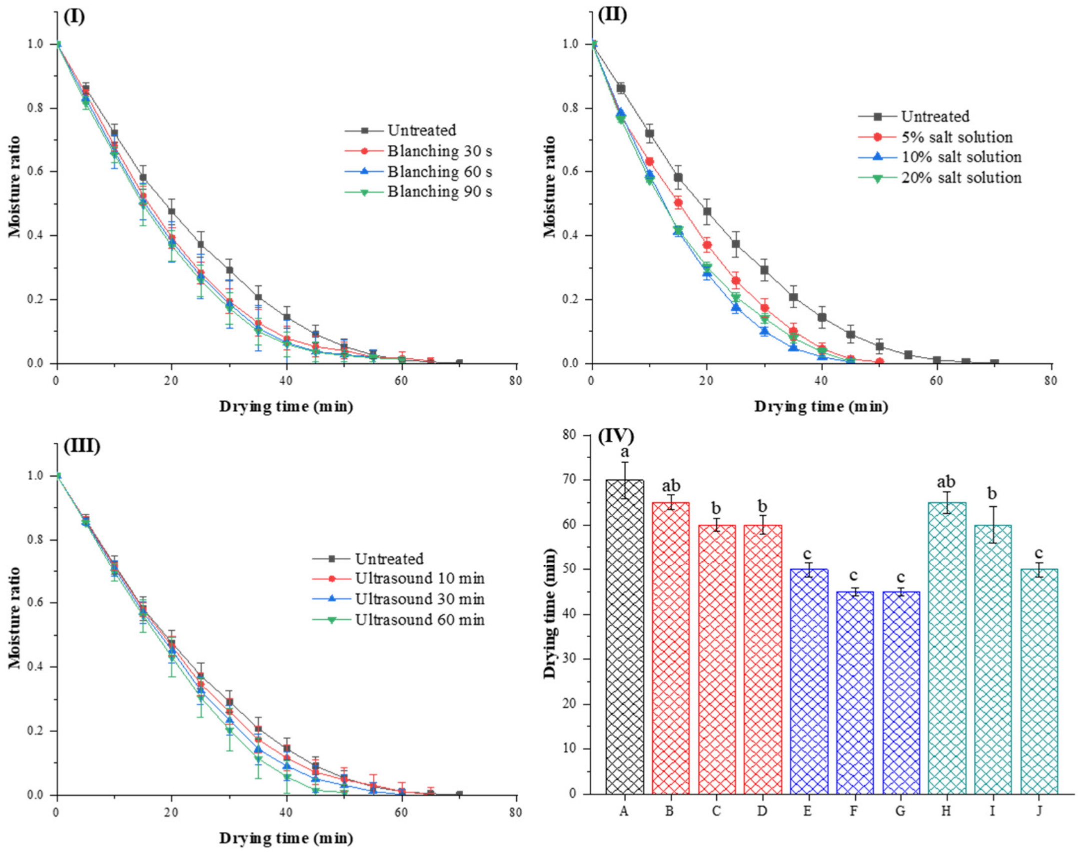

Figure 2. Drying curves and drying time of potato slices under different pretreatment conditions such as (**I**) blanching, (**II**) saline immersion, and (**III**) ultrasound pretreatment. (**IV**) The drying time for (A) untreated potato samples, (B–D) with blanching pretreatment for 30, 60, and 90 s, (E–G) with saline immersion under solution concentration of 5%, 10%, and 20%, and (H–J) with ultrasound pretreatment for 10, 30, and 60 min. Means denoted by a different lowercase letter indicate significant difference between treatments ($p < 0.05$).

The effect of ultrasound time on the drying time is shown in Figure 2III. It was found that the drying times were about 65, 60, and 50 min for the potato samples treated for 10, 30, and 60 min, respectively. This may be due to cell disruption and microscopic channels being formed after ultrasound pretreatment, which led to a reduction in the resistance against moisture migration [43].

Figure 2IV shows the drying time and variance analysis results of the potato slices under different pretreatment conditions. All three pretreatments enhanced the drying kinetics relative to the untreated samples The saline immersion pretreatment had the greatest influence on the drying time, followed by the ultrasound and blanching pretreatments. In general, the different pretreatments had different effects on the structure of the materials and further affected the process of heat and mass transfer during the drying.

3.2. Three-Dimensional Appearance Characterization

The 3D appearance images of the dried potato slices under different pretreatments are shown in Figure 3. The three images from top to bottom in each column represent the physical, 3D reconstruction, and height distribution diagrams of the potato slices. It was found that the appearance of the potato slices had significant curling, shrinkage, and browning after the drying process. Moreover, the appearance of the dried potato slices varied greatly with different pretreatments.

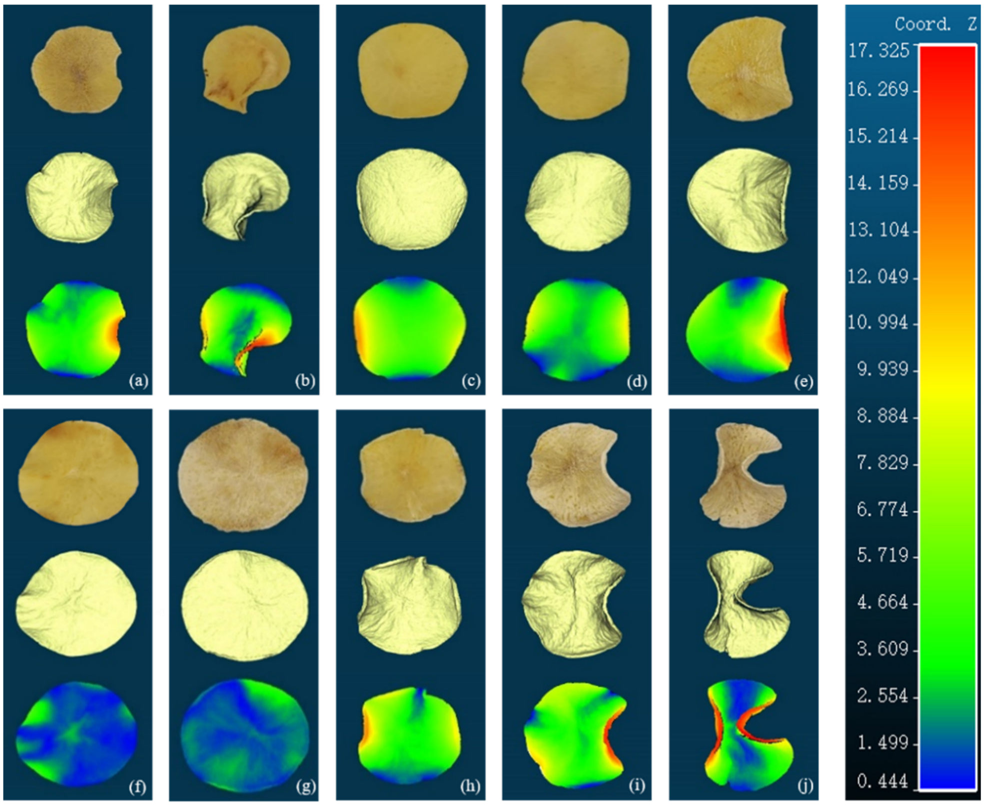

Figure 3. Three-dimensional appearance images of dried potato slices under different pretreatments. (**a**) Untreated potato samples. (**b**–**d**) Blanching pretreatment for 30, 60, and 90 s. (**e**–**g**) Saline immersion under solution concentration of 5%, 10%, and 20%. (**h**–**j**) Ultrasound pretreatment for 10, 30, and 60 min. The three images from top to bottom in each column represent the physical, three-dimensional reconstruction, and height distribution diagrams of the potato slices.

Figure 3b–d shows the appearance of the potato slices after pretreatment by blanching for 30, 60, and 90 s, respectively. When the blanching time was 30 s, the dried potato slices curled obviously. However, when the blanching time was extended to 60 s or 90 s, the potato slices became relatively flat. It has been reported that blanching can destroy the cellular structure and alter the moisture distribution of materials, which leads to a more uniform moisture distribution in materials [44]. The uniform distribution of moisture in the material could have reduced the stress caused by shrinkage in the drying process.

The appearance of the potato slices after pretreatment by saline immersion under solution concentrations of 5%, 10%, and 20% is shown in Figure 3e–g. It can be seen from the figures that, as the salt solution concentration increased to 10% and 20%, the saline immersion pretreatment obviously inhibited the shrinkage and curling of the potato slices during drying. The reason for this phenomenon may be that salt particles could fill the spaces reduced by moisture removal during the drying process. In contrast, for the samples pretreated by ultrasound pretreatment, especially for a long time (60 min), the appearance of the material was seriously curled. This may be attributed to the destruction of the material structure by the “cavitation effect” of ultrasound.

In summary, saline immersion and blanching pretreatment could effectively inhibit the shrinkage and curling of the potato slices, while ultrasound pretreatment aggravated the deformation during the drying process.

3.3. Shrinkage

The shrinkage curves of potato slices under different pretreatment conditions during drying process are shown in Figure 4I–III, and the results of the analysis of variance of the dried potato slices are shown in Figure 4IV. It can be seen that the shrinkage of the potato slices mainly took place at the early drying stage, and gradually slowed down in the later drying stage. It has been reported that the shrinkage at the initial stage of drying is approximately equal to the volume of moisture lost, while in the middle and late drying stages, with the fixation of the "skeleton", the shrinkage becomes slow [45].

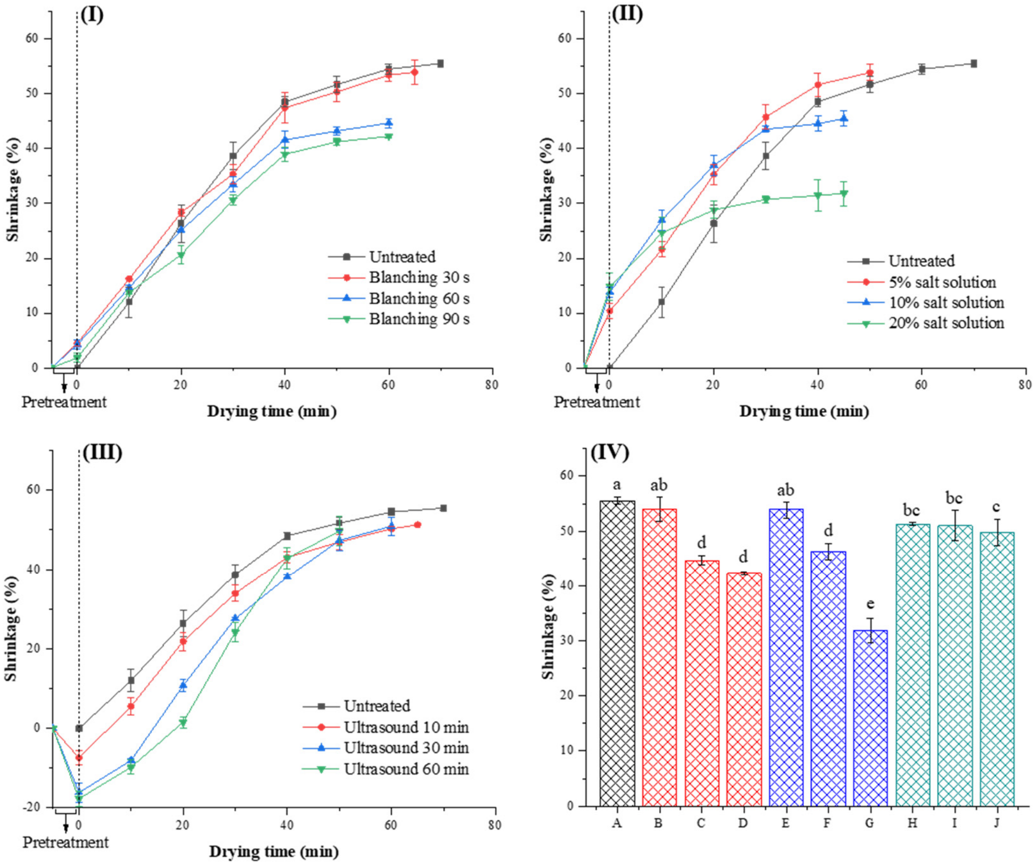

Figure 4. Shrinkage of potato slices during drying under different pretreatments, such as (**I**) blanching, (**II**) saline immersion, and (**III**) ultrasound pretreatment. (**IV**) The shrinkage for (A) untreated potato samples, (B–D) with blanching pretreatment for 30, 60, and 90 s, (E–G) with saline immersion under solution concentration of 5%, 10%, and 20%, and (H–J) with ultrasound pretreatment for 10, 30, and 60 min. Means denoted by a different lowercase letter indicate significant difference between treatments ($p < 0.05$).

As shown in Figure 4I, the blanching time had a great influence on the shrinkage of the potato slices. The shrinkage of the dried potato slices at 30, 60, and 90 s were 53.97%, 44.67%, and 42.27%, respectively, which decreased by 2.83%, 19.57%, and 23.89% compared with the untreated samples (55.54%). This was because the blanching caused the cell walls to collapse [46], which reduced the effect of surface stress. Mahiuddin et al. [47] also reported that the destruction of the cell structure has an effect on the shrinkage properties of materials.

Figure 4II indicates the shrinkage of the potato slices by saline immersion under different solution concentrations. It can be seen that the saline immersion pretreatment had a great influence on the shrinkage of the dried potato slices. The shrinkage of the potato slices decreased with the increase in the salt solution concentration. The potato slices had minimal shrinkage when the salt solution concentration reached 20%, which caused a decrease of 42.69% compared to the untreated sample. Fante et al. [48] found that an increase in sucrose solution concentration led to a decrease in the shrinkage of dried plum slices in the drying process. This may be due to the fact that salt or sucrose particles can fill the space left by the removal of moisture in the material, which would support the skeleton structure of the material to a certain extent.

From Figure 4III, it was found that the ultrasound pretreatment slightly reduced the shrinkage, but the pretreatment time had no significant effect on the shrinkage of the dried potato slices. Liu et al. [49] observed large microchannels and pores in ultrasound-pretreated samples, while the structure of the untreated material was relatively compact. In addition, ultrasound waves may have extended the intercellular spaces by the cavitation effect [50], which may have partially offset the volume reduction caused by moisture removal.

3.4. Height Standard Deviation (HSD)

The curling degree was evaluated by the HSD of the material surface. The HSD curves of the potato slices during drying under different pretreatments are shown in Figure 5. At the early stage of drying, the HSD of the material changed little or showed a downward trend, which was mainly due to the softening of the material structure by hot-air heating. The HSD increased rapidly in the middle and late drying stages, indicating that the material had an obvious curling phenomenon. The shape changes in the materials in the drying process may be due to the uneven stress caused by the shrinkage of the cells and pores [51].

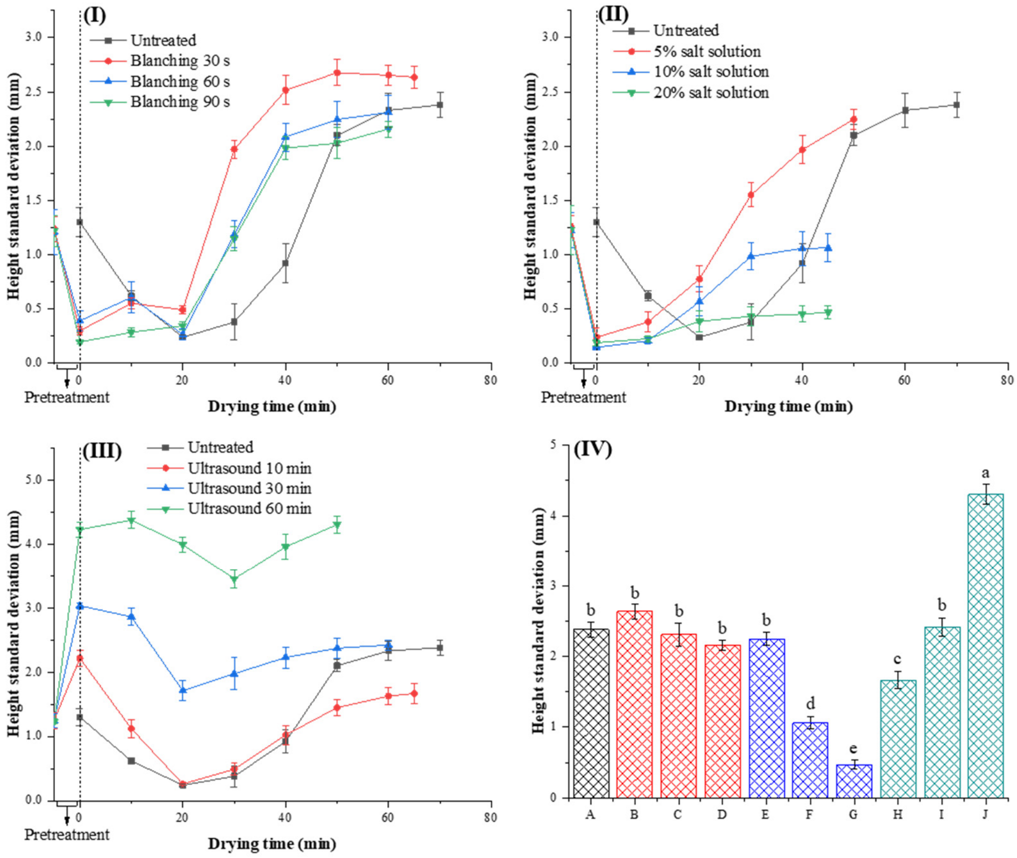

Figure 5. Height standard deviation of potato slices during drying under different pretreatments, such as (**I**) blanching, (**II**) saline immersion, and (**III**) ultrasound pretreatment. (**IV**) The height standard deviation for (A) untreated potato samples, (B–D) with blanching pretreatment for 30, 60, and 90 s, (E–G) with saline immersion under solution concentration of 5%, 10%, and 20%, and (H–J) with ultrasound pretreatment for 10, 30, and 60 min. Means denoted by a different lowercase letter indicate significant difference between treatments ($p < 0.05$).

The HSD of the dried potato slices after blanching for 30, 60, and 90 s were 2.64 mm, 2.31 mm, and 2.16 mm, respectively. However, there was no significant difference between the blanching pretreatment and the untreated samples, indicating that the blanching pretreatment could not reduce the curling phenomenon during drying. Although the structure of the material would have been damaged by the blanching process, the starch gelatinization caused by the high temperature may have played a certain role in supporting the structure.

As shown in Figure 5IV, the HSD of the dried potato slices after saline immersion pretreatment under solution concentrations of 5%, 10%, and 20% were 2.25 mm, 1.06 mm, and 0.47 mm, respectively, which decreased by 5.88%, 55.46%, and 80.25% compared with the untreated samples. The results demonstrated that saline immersion could inhibit the curling of the potato slices in the drying process, showing a relatively flat shape. This may be because osmotic ions entered the tissue and blocked the transmission of internal stress [52]. In addition, it also may have been due to the structure of "hard outside and soft inside" after processing by osmotic dehydration [53].

For the ultrasound pretreatment, the HSD after ultrasound pretreatment for 10, 30, and 60 min were 1.67 mm, 2.41 mm, and 4.30 mm, respectively. It was found that ultrasound pretreatment for 10 min could reduce the HSD of the potato slices, which indicated that a shorter time of the ultrasound pretreatment could reduce the curling degree. When the ultrasound time was extended to 60 min, the HSD (4.30 mm) increased by 80.67% compared with the untreated samples, which indicated that very serious curling of the slices occurred. This may be because the short-time ultrasound pretreatment made the potato tissue more uniform, thereby resulting in a more uniform transfer of internal stress. However, with the increase in the ultrasound time, the cavitation effect of micro-jets and micro-agitation at the bubble inter-face led to the destruction of the cell structure and formed cracks and pores [54]. The non-continuous and non-uniform structure increased the effect of stress and showed the appearance of curling from a macroscopic perspective.

3.5. Color

Color is a significant quality parameter of dried potato slices, which influences the customer's perception and purchasing power [55]. The color values of all the samples are presented in Table 1. Blanching, saline immersion, ultrasound, and drying had significant effects on the color parameters of the dried potato slices. As seen in Table 1, the L^*, a^*, and b^* values of the untreated potato slices were 72.62, 8.24, and 26.13, respectively. It was found that the untreated samples had the largest value of ΔE, which was due to browning caused by the drying process [56]. The L^* value of the potato slices pretreated with blanching was lower, which may be related to the gelatinization of starch by blanching pretreatment. Xiao et al. [57] reported that the clarity of gelatinized starch could reduce the lightness of starch products. Compared with the untreated samples, the values of a^* and b^* were significantly reduced. The value of ΔE of the dried samples after blanching pretreatment was also significantly lower than that of the untreated samples. In particular, when the blanching time was 30 s, the color change was the least, and the ΔE value was 3.10. This indicated that blanching pretreatment could better retain the original color, which may be because blanching inactivates polyphenol oxidase. It has also been reported that this phenomenon is due to the leaching of reducing sugars by blanching pretreatment, which is the substrate of the Maillard reaction [58]. Thus, this minimized the non-enzymatic browning reaction and reduce the color variation in the slices.

The effect of the saline immersion pretreatment on the color is shown in Table 1. The values of L^*, a^*, and b^* were all smaller than those of the untreated samples. With the increase in the salt concentration, the value of the sample color parameters decreased continuously, which indicated that a high concentration salt solution could achieve a better retention effect in terms of color. This may be due to the loss of polyphenol oxidase, which is due to the leakage effect of a high-concentration salt solution.

For the ultrasound pretreatment, the color parameters of the potato slices were slightly less than those of the untreated samples. With the extension of the ultrasound time, the ΔE value gradually decreased, which indicated that long-time ultrasound pretreatment was in favor of maintaining the color of the samples. This may be because the ultrasound pretreatment reduced the oxygen content of the sample and inhibited the browning reaction [38,59].

Table 1. Changes in color, total polyphenol content, and antioxidant capacity of potato slices after drying under different pretreatments.

Pretreatment Methods		L^*	a^*	b^*	ΔE	TPC (mg/g)	DPPH Radical Scavenging Activity (%)
Untreated	-	72.67 ± 0.48 ^{a}	8.24 ± 0.09 ^{a}	26.13 ± 0.18 ^{a}	24.60 ± 0.91 ^{a}	0.31 ± 0.02 ^{d,e}	34.12 ± 1.51 ^{c}
Blanching	30 s	51.35 ± 1.13 ^{e,f}	4.44 ± 0.07 ^{f,g}	15.83 ± 0.33 ^{e}	3.45 ± 0.50 ^{f}	0.45 ± 0.05 ^{a}	56.45 ± 1.02 ^{a}
	60 s	50.50 ± 0.69 ^{e,f}	5.02 ± 0.36 ^{e,f}	17.88 ± 0.63 ^{d}	5.54 ± 0.37 ^{e,f}	0.42 ± 0.03 ^{a,b}	52.01 ± 3.94 ^{a}
	90 s	49.89 ± 1.01 ^{f}	6.10 ± 0.34 ^{c,d}	18.20 ± 0.20 ^{d}	6.17 ± 0.98 ^{e,f}	0.32 ± 0.02 ^{c,d}	38.82 ± 3.66 ^{c}
Saline immersion	5%	67.28 ± 1.44 ^{b}	7.09 ± 0.67 ^{b}	27.01 ± 2.22 ^{a}	20.82 ± 2.44 ^{b,c}	0.27 ± 0.04 ^{e,f}	26.38 ± 0.81 ^{d}
	10%	63.12 ± 1.26 ^{c}	7.10 ± 0.57 ^{b}	20.29 ± 0.44 ^{c}	13.42 ± 1.41 ^{d}	0.28 ± 0.03 ^{d,e}	25.08 ± 0.90 ^{d}
	20%	59.81 ± 0.71 ^{d}	5.31 ± 0.43 ^{d,e}	17.03 ± 0.63 ^{d,e}	8.68 ± 1.32 ^{e}	0.22 ± 0.02 ^{g}	17.15 ± 1.30 ^{c}
Ultrasound	10 min	72.23 ± 0.31 ^{a}	6.49 ± 0.22 ^{b,c}	26.01 ± 1.10 ^{a}	23.97 ± 1.48 ^{a,b}	0.40 ± 0.05 ^{b}	46.72 ± 3.13 ^{b}
	30 min	71.92 ± 0.71 ^{a}	5.87 ± 0.21 ^{c,d}	23.44 ± 1.26 ^{c}	22.34 ± 1.79 ^{a,b,c}	0.35 ± 0.04^{c}	45.07 ± 2.19 ^{b}
	60 min	70.86 ± 1.88 ^{a}	5.44 ± 0.39 ^{d,e}	21.30 ± 0.62 ^{c}	20.40 ± 2.08 ^{c}	0.22 ± 0.03 ^{f,g}	33.65 ± 0.98 ^{c}

Note: Data are expressed as the average ± standard deviation for three replicates. Values in the same column with different letters for each parameter are significantly different ($p < 0.05$).

3.6. Total Polyphenol Content (TPC)

The effects of the different pretreatment methods on the TPC of the dried potato slices are shown in Table 1. Compared with the untreated samples, the blanching and ultrasound pretreatment had a better retention of polyphenols, while the saline immersion pretreatment was not conducive to the retention of polyphenols.

Compared with the untreated samples, the total polyphenol content in the blanching-pretreated samples was generally increased. However, with the extension of the blanching time, the total polyphenol content gradually decreased. This indicated that short-time blanching pretreatment was beneficial to the retention of polyphenols. This may be due to the loss of polyphenol oxidase activity by blanching pretreatment, which resulted in a better retention of more polyphenols [59]. However, a prolonged blanching time made the cellular structure vulnerable to damage during drying, which led to the oxidation of polyphenols [40].

For the samples treated with saline immersion, the content of polyphenols was lower than that of the untreated samples. When the solution concentration reached 20%, the polyphenol content was the lowest. This was the loss of polyphenols due to leakage of the salt solution [60,61].

Similar to the blanching pretreatment, a shorter ultrasound treatment was more beneficial for polyphenol retention. This may be due to the fact that ultrasound pretreatment can produce stomata in plant tissues, thus improving the extraction of polyphenols during the preparation of sample [62]. However, when the ultrasound time was too long, the total phenol content decreased slightly, which was due to the loss of food ingredients caused by the enlargement of pores [63]. This was consistent with the study of polyphenol content in dried onions slices by Ren et al. [64].

3.7. DPPH Radical Scavenging Assay

The DPPH free radical activity values of the dried potato slices under different pretreatments are shown in Table 1. It was observed that the trend of DPPH was similar to that of TPC retention. The high positive correlation between phenolic compounds and antioxidant activity was also reported in another study [65]. In this study, the free radical scavenging activity of the blanched samples was the best, followed by the samples pretreated with ultrasound and saline immersion. When the blanching time was 30 s, the sample showed the highest activity (56.45%), which was similar to the results of Feng et al. [66].

3.8. Microstructure

The scanning electron microscopy (SEM) images of the dried potato slices under different pretreatments are shown in Figure 6. The microscopic results of the different pretreated samples and untreated samples differed greatly. As shown in Figure 6a, the untreated samples had both dense and porous structures, which may be caused by the non-uniform shrinkage of the material structure. From Figure 6b, we also found intact starch granules, indicating that the starch did not swell and gelatinize during the drying process.

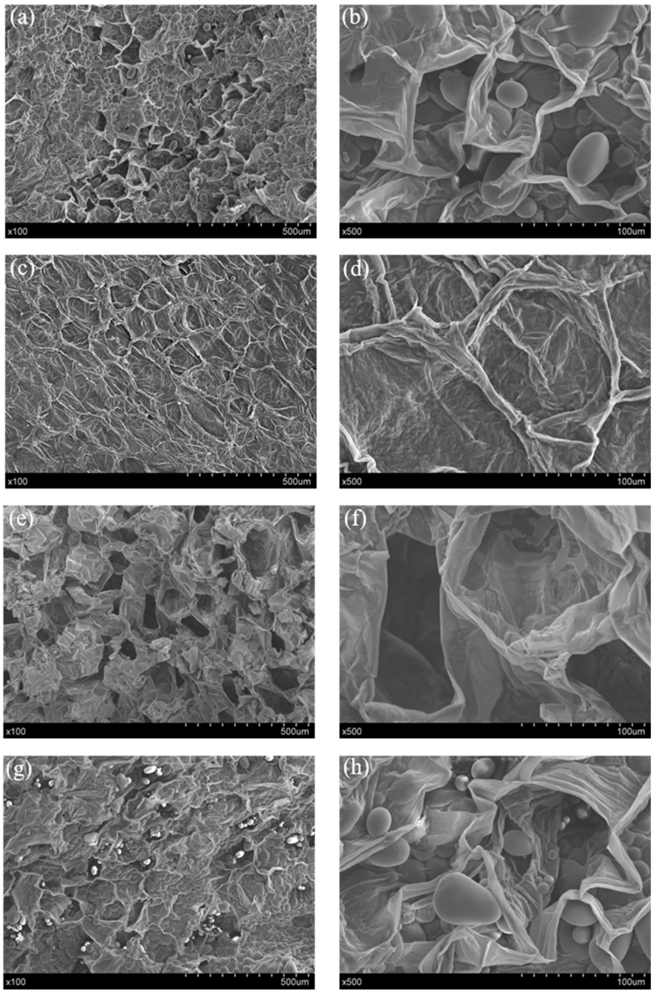

Figure 6. Microstructures of dried potato slices under different pretreatments in different magnifications. (**a**,**b**) Untreated potato samples; (**c**,**d**) blanching pretreatment for 90 s; (**e**,**f**) saline immersion under solution concentration of 20%; and (**g**,**h**) ultrasound pretreatment for 60 min.

The microstructure of the dried samples after blanching pretreatment are shown in Figure 6c,d. The tissue structure of the blanched dried potato slices was uniform and dense, and no obvious pore structure was found. This may be caused by the collapse of the cellular structure after the blanching and drying process. In addition, starch granules were not found in the micrograph field, indicating that the blanching treatment resulted in starch breakage and gelatinization [46]. This was similar to the results of a study on sweet potato bars [57].

The samples from the saline immersion pretreatment had a relatively loose and porous structure (Figure 6e,f). The cytoskeletal structure became coarse as compared to the untreated samples, and starch granules were no longer visible in the samples. This may be due to the internal modification of the starch particles by the components of osmotic solution during processing [67]. After the ultrasound pretreatment, the boundaries of the cells were fuzzy, while the starch granules could be also clearly seen (Figure 6g,h). This was because the ultrasound pretreatment caused changes in the cell structure and formed microchannels on the surface of the potato samples, and the microchannels were combined with the original pore structure, which may be due to the cavitation and sponge effects of the ultrasound waves [68]. The observation of the microstructure of the material was helpful in understanding the effects of pretreatment on the drying rate and appearance deformation.

4. Conclusions

The application of blanching, saline immersion, and ultrasound pretreatment had significant effects on the drying characteristics, 3D appearance, quality characteristics, and microstructure of the potato slices. The results showed that pretreatment significantly enhanced the drying process of the potato slices and affected the 3D appearance during drying. All the pretreatment methods reduced the shrinkage during the drying process relative to the untreated potatoes. The curling degree was quantitatively characterized by height standard deviation (HSD). The results showed that the saline immersion and blanching pretreatments inhibited the curling of the potato slices, while the ultrasound pretreatment greatly aggravated the curling.

Through the quality analysis of the dried potato slices, it was found that the color difference value, total polyphenol content, and antioxidant activity of the potato slices were significantly different under the different pretreatment conditions. The blanching pretreatment could significantly inhibit color deterioration and maintain a higher total polyphenol content and antioxidant activity. Although the blanching pretreatment could significantly improve the nutritional quality and color of the potato slices, it could not significantly reduce the curling degree. Therefore, blanching pretreatment combined with saline immersion may be an optimal alternative pretreatment method for potato slice drying.

The microstructures of the dried potato slices were observed and analyzed by SEM. The microstructures of the dried potato slices were significantly changed under the different pretreatments, which was helpful in understanding and verifying the effects of pretreatment on the drying kinetics and appearance deformation. In addition, the mechanism of the 3D appearance changes caused by pretreatment needs to be further studied. This paper can provide a certain reference for the 3D appearance change and control of agricultural products during the drying process.

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