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Influence of different pretreatments on the quality attributes of heat pump dried beetroot slices

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Abstract

This research investigates the effects of different pretreatments, including ultrasound (US), steam blanching (SB), osmotic dehydration (OD) and freeze-thaw (FT), on the quality characteristics of heat pump dried beetroot slices. The physicochemical properties, phytochemical compositions, and antioxidant capacity of heat pump dried beetroot slices were analyzed. In terms of physicochemical properties, the dried beetroot slices pretreated by FT showed the lowest drying time of 215 min and the highest rehydration ratio of 7.31. The dried beetroot slices pretreated by SB exhibited the highest hardness, shrinkage rate, and bulk density, namely 1574.9 g, 93.38 %, and 1.29 g/mL, respectively. Additionally, the samples pretreated by US effectively preserved the original microstructure of beetroot slices and showed the most attractive red color with a^* value of 31.36. Regarding phytochemical compositions, SB resulted in the higher preservation of betalains, TPC, and TFC than other pretreatments. Compared to CK, the four pretreatments all significantly improved the ascorbic acid content of dried beetroot slices ($p < 0.05$), and SB led to the highest ascorbic acid content of 342.28 mg/100 g dm. Concerning antioxidant capacity, SB displayed higher retention of FRAP value and ABTS radical scavenging activity of dried beetroot slices compared to other pretreatments. Our findings indicate that SB is a promising pretreatment to improve drying process and quality characteristics of heat pump dried beetroot slices.

Keywords: Beetroot slices, Ultrasound, Steam blanching, Freeze-thaw, Antioxidant capacity, Heat pump drying

Introduction

Beetroot (*Beta vulgaris* L.) is a biennial tuberous plant mainly cultivated in Europe and Asia, belonging to the *Chenopodiaceae* family[1]. Beetroot not only provides valuable essential nutrients, but also is culture-rich in multiple bioactive phytochemicals, such as betalains, phenolic acids, triterpenes, carotenoids, and flavonoids[2]. These compounds endow beetroot with a wide range of biological activities, including antioxidant, antimicrobial, anti-inflammatory, anti-hypertensive, hypoglycemic, hepatoprotective, anti-depressant, and hypolipidemic activities[3]. So beetroot can be utilized as functional food source against many diseases, such as cancer, cardiovascular disease, diabetes and various other oxidative stresses induced chronic diseases[4]. Beetroot contains a high amount of inorganic nitrate (NO_3^-), it has been found that beetroot intake may be an effective tool to improve oxidative metabolism and muscle force production in combat sports athletes[5]. Beetroot is considered as a blessing for the food industry and also used as food coloring agent or additive in food products[6]. Fresh beetroots are exposed to spoilage due to its high moisture content.

One of the important preservation methods ensuring microbiological safety of products is drying. Drying can help preserve or even improve the nutrient content and physicochemical properties of beetroot products. Drying methods have significant impacts on antioxidant capacity and bioaccessibility of phytochemicals in beetroots. The influence of drying methods on the quality attributes of freeze-thaw pretreated beetroots were investigated[7], and the results suggested that microwave-vacuum drying is a more beneficial drying method for freeze-thaw pretreated beetroots. Conventional drying, vacuum freeze drying, and spray drying were used for beetroot dehydration, and the results showed that the samples treated by higher temperature contained lower contents of total phenol and betacyanins[8]. Heat pump drying (HPD) based on the reverse Carnot cycle principle, by using both the heat source of the condenser and the heat sink of the evaporator, the drying process can be conducted with a low energy consumption[9]. Compared with traditional drying technologies, HPD has the characteristics of simple operation, low cost, good quality of dried products, and environmental friendliness[10]. As a highly effective method at low temperatures, HPD is especially suitable for the temperature sensitive vegetables and fruits[11]. It was reported that microwave vacuum drying and microwave drying required shorter drying times than vacuum drying, heat pump drying and freeze drying, and beetroots prepared by heat pump drying illustrated the highest contents of betalains and total flavonoids[12].

Apart from drying techniques, employing proper pretreatment prior to drying can accelerate internal moisture migration, improve the quality of dehydrated products, enhance process efficiency, as well as reduce excessive energy consumption[13]. Commonly utilized pretreatments comprise ultrasound, freeze-thaw, steam blanching, and osmotic dehydration. Ultrasound (US) can provide mechanical energy, causing periodic compression and expansion, which is similar to the found in a sponge when continuously pressing and relaxing called the “sponge effect”[14]. US enhances the migration of moisture and material transport within fruits and vegetables, thus accelerating the drying process and improving its uniformity[15]. Ultrasound-assisted drying retained the original color, and betalain retention of red beetroot was approximately 15 % higher than hot air drying, and reduced the drying time by approximately 55 % as compared to hot air drying[16]. The application of the ultrasound probe (direct) and ultrasound bath (indirect) in the production of oven-dried beetroot snacks reduced the total processing time by 26 % and 24 %, respectively[17]. Freeze-thaw (FT) as a pretreated technique, it freezes foodstuffs to the freezing point and then thaws it. During the FT process, the water in the cellular foods crystallizes and convert into ice crystals, which can damage the cellular structures and improve the water migration[18]. It was reported that freeze-thaw could prompt more efficient drying, improve heating uniformity, and display undesirable effects on color, shrinkage, betalains, phenolics and ABTS scavenging activity of red dragon fruit[19]. Blanching is an essential heat treatment for many fruits and vegetables processing, which can inactive the quality deterioration enzymes and destroy microorganisms that might contaminate raw fruits and vegetables during harvesting, production, transportation and storage[20]. At present, steam blanching and hot water blanching are the two most common methods. Hot water blanching method is easy to operate. However, it has several drawbacks, such as the loss of nutrients, especially water-soluble nutrients, due to leaching and diffusion during the blanching process. Furthermore, hot water blanching requires a large amount of water and generates an excessive amount of wastewater[21]. Steam blanching (SB) can prevent the loss of water-soluble nutrients due to leaching, and the wastewater generated during the blanching process is very little. However, it also has several disadvantages, such as uneven heating, low heat transfer, and unsuitability for large quantities of materials[22]. Blanching has been reported to be an effective pretreatment for beetroot prior to drying. In a study by Chaudhary and Kumar[23], water blanching and steam blanching were effective pretreatments to reduce drying time, improve swelling capacity, water absorption capacity, oil absorption capacity, foam capacity, foam stability, bulk density and greater functional properties of beetroot powder compared to other pretreatments. Osmotic dehydration (OD) as a pretreatment for drying, by immersion in aqueous solutions with high osmotic pressure, which can remove water while increasing the number of soluble solids[24]. There are various forms of osmotic agents, the most commonly used being sodium chloride and glucose. It was confirmed that osmotic dehydration not only decreased the drying time by up to 32 % but also resulted in dried Iranian quince slices exhibiting greater antioxidant activity, total phenolic content, and vitamin C compared to fresh samples[25]. Layeghinia et al.[26] found that microwave-dried *Allium hirtifolium* Boiss subjected to osmotic pretreatment showed lower total color difference and browning index and higher rehydration ratio compared to ultrasound-assisted osmotic pretreatment. The osmotic dehydration conditions of beetroots in sugar beet molasses were optimized, and the favorable drying parameters were selected with temperature of 60 °C, molasses concentration of 70 %, and processing time of 5 h[27]. OD and US have been explored to improve dried beetroot chips' nutritional quality and sensory characteristics[28]. The effects of blanching, ultrasonic processing and freezing conditions on quality properties of freeze-dried red beets were investigated, and results indicated that quick freezing resulted in the freeze-dried red beets with the lowest shrinkage and best porosity[29]. The beetroot was exposed to ethanol immersion, ultrasound, ultrasound-ethanol immersion, microwave, steam blanching, water blanching, and starch-blanching prior to hot air drying, and results showed that ultrasound-ethanol immersion and starch-blanching could be used to improve the drying characteristics of beetroots at an industrial scale[30]. It has been reported by Mudgal et al.[31] that the effect of different pretreatments on the quality attributes of beetroot chips, and the results revealed that blanching plus potassium metabisulphite pretreated beetroot chips showed the highest sensory scores.

Although the above four pretreatment methods have been applied to beetroots before drying, the current literature displayed that these pretreatments have not been applied to heat pump drying of beetroot slices yet, and it is also unclear how these pretreatment methods affect the quality characteristics of heat pump dried beetroots. Therefore, this research set out to explore the effect of various pretreatments, including ultrasound (US), steam blanching (SB), osmotic dehydration (OD) and freeze-thaw (FT), on the quality attributes (physicochemical properties, phytochemical compositions, and antioxidant capacity) of heat pump dried beetroot slices. The study results offer an efficient pretreatment for the beetroot slices before drying, thereby providing a theoretical basis for developing high quality and nutritional content for dried beetroot products.

Materials and methods

Materials

The harvest period for beetroots is from September to November every year. Fresh beetroots (*Beta vulgaris* L. *var. conditiva Alef.*) were sourced from a local market in Xuzhou, Jiangsu Province, China in November 2023. The weight of a beetroot was about 500 g and the average initial moisture content of beetroot was 85.21 % (wet basis, w.b.). Beetroots with uniform length and size were stored in a refrigerator at 4 °C before use.

Pretreatments

Fresh beetroots were washed, peeled and then cut into circular slices with 3 mm in thickness and 7 mm in diameter using a stainless steel slicer and circular grinding tool. The fresh beetroot slices with initial moisture content of 85.21 % (w.b.) were subjected to four different pretreatments. US pretreatment: Beetroot slice samples were put into a polyethylene bag and immersed into distilled water placed in an ultrasonic instrument (KQ-500Z, Kunshan Shumei Ultrasonic Instrument Co., Ltd, Jiangsu, China). Beetroot slice samples were subjected to ultrasonic waves at frequency of 28 kHz and power of 200 W for 30 min. SB pretreatment: Steam blanching was conducted by exposing beetroot slice samples to steam without direct contact with the boiling water. Beetroot slice samples were placed in an inner vessel with the steam circulating inside the vessels as the outer vessel was completely covered with a lid. The steam blanching temperature was about 95 °C, and the steam blanching time was 5 min. Allowing the blanched beetroot slices to cool naturally, then wiped off the excess water at the surface of beetroot slices with absorbent paper. FT pretreatment: Beetroot slice samples were put into a polyethylene bag and put them into a refrigerator at –20 °C to freeze for 12 h, then thawed them with running water (about 25 °C) for 30 min. At last, the excess water at the surface of beetroot slices was wiped off with absorbent paper. OD pretreatment: The osmotic treatment was carried out in a 5.0 L beaker and covered with a piece of plastic film. Beetroot slice samples were immersed into 55.0 % sucrose solution for osmotic dehydration. The ratio of the sample to the osmotic solution was 1:2 (w/w). The osmotic dehydration process was performed at 20.0±1.0 °C for 2.5 h, and then the excess water at the surface of beetroot slices were wiped off using absorbent paper.

Drying procedure

The ultrasound pretreated beetroot slices, steam blanching pretreated beetroot slices, freeze-thaw pretreated beetroot slices, and osmotic dehydration pretreated beetroot slices were evenly dispersed in trays and dried in a heat pump dryer (L3.5AB, Guangdong IKE Industrial Co. Ltd, China) with a temperature of 60 °C. The beetroot slices dried by heat pump dryer without any pretreatment were recognized as control group (CK). Moisture content of beetroot slices was measured throughout the entire heat pump drying process until the moisture content was below 8.0 % (w.b.). Then the drying process was stopped, thus the total drying time can be determined. Each drying experiment was repeated three times. After drying, the dried beetroot slices were put into packaging bags, and then determined the quality properties.

Determination methods

Rehydration property

The rehydration ratio was measured according to the method reported by Bozkir and Ergün[32]. 2 g of dried beetroot slices were placed in a 250 mL flask with 200 mL distilled water for 15 min at temperature of 80 °C. Thereafter, the rehydrated beetroot slices were blotted with absorbent paper to remove excess water before weighing. The rehydration ratio (*RR*) was calculated using the following equation：

$$RR = \frac{W_2}{W_1} \tag{1}$$

where W_1 denotes the weight of dried beetroot slice samples, g, W_2 represents the weight of beetroot slice samples after rehydration, g.,

Hardness

The texture of dried beetroot slices was expressed in terms of hardness, and evaluated by a texture analyzer (TA.XT plus, Stable Micro Systems Ltd., Godalming, UK) using a penetration test, equipped with a cylinder probe P/2 (2 mm in diameter). The pretest and test speed were set at 2.0 and 2.0 mm/s, respectively. The post-test speed was 10.0 mm/s, and the test distance was set at 10 mm with a trigger force of 5.0 g. Ten replicates for each group were conducted.

Shrinkage rate

Determination of sample volume by solid displacement method with superfine quartz sand. 10.0 g of dried beetroot slices and 100 mL of superfine quartz sand were packed into a measuring cylinder and then compacted. The shrinkage rate (*SR*) was calculated using the Equation (2)[33].

$$SR = \frac{V_0 - V_1}{V_0} \times 100\% \tag{2}$$

where V_0 is the volume of fresh beetroot slices, mL, V_1 is the volume of dried beetroot slices, mL.

Bulk density

Three grams of dried beetroot slices were weighed and placed into a 10 mL graduated cylinder. The dried beetroot slices were oscillated with a vortex oscillator for 2 min to stabilize the volume. The volume of dried beetroot slices was recorded, and the bulk density was calculated by dividing the sample weight by its volume according to the following equation[34]:

$$\rho = \frac{m}{V} \tag{3}$$

where ρ is bulk density, g/mL, m is the mass of dried beetroot slices, g, V is the volume of dried beetroot slices, mL.

Color analysis

Color parameters of fresh beetroot slices and dried beetroot slices were measured using a handheld colorimeter (CR-400, Minolta Konica Inc., Osaka, Japan), which is based on CIE system and provides L^*, a^*, and b^* parameters. L^* represents lightness, 0–black, 100–white. a^* indicates greenness or redness ranging from -60 (green) to 60 (red). b^* shows blueness or yellowness ranging from -60 (blue) to 60 (yellow). The results of samples were averaged eight measurements. Chroma (C) denotes the saturation of the color, which is the quantitative attribute of colorfulness. Hue angle ($H°$) represents the color nuance and defines as follows: 0° (red), 90° (yellow), 180° (green), 270° (blue)[35]. The total color difference (ΔE), C, and $H°$ were calculated according to Equation (4), Equation (5), and Equation (6), respectively.

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (4)$$

$$C = \sqrt{a^{*2} + b^{*2}} \quad (5)$$

$$H° = \arctan\left(\frac{b^*}{a^*}\right) \quad (6)$$

Where L^*, a^*, and b^* are the values of dried beetroot slices, L_0^*, a_0^*, and b_0^* are the values of fresh beetroot slices.

Microstructure analysis

Microstructure was observed by a thermal emission scanning electron microscope (Gemini 300, Carl Zeiss AG, Oberkochen, Germany). Dried beetroot slice samples were observed the center along the cross section. The scanning was done at 5.0 kV accelerating voltage and imaged at 100 magnifications.

Extraction procedure

In order to evaluate the phytochemical compositions and antioxidant capacity, the dried beetroot slices were ground using a high-speed crusher and passed through a 60-mesh sieve to obtain beetroot powder. Beetroot powder (2.0 g) with an accuracy weight was dissolved with 20 mL of 50 % ethanol solution. Supernatant was collected after centrifugation at 5000 rpm for 15 min. The extraction procedure was repeated twice more. The supernatants obtained from three extractions were transferred into a 100 mL volumetric flask to set the volume with 50 % ethanol solution. The extract was stored at 4 °C for subsequent determination of phytochemical compositions and antioxidant properties.

Betalain content

Betalains content was determined using the colorimetric method described by Stintzing et al.[36] with appropriate modifications. The extract was diluted with 0.05 M phosphate buffer solution (pH 6.5) to obtain absorption values ranged from 0.8 to 1.0 at 538 nm. Then the absorbance of the diluted extract was read at λ = 540 nm for betacyanin (*BC*), at λ = 480 nm for betaxanthin (*BX*), and at λ = 600 nm for impurities. The outcomes were calculated using Equation (7).

$$BC/BX\,(\mathrm{mg/g\,dm}) = \frac{(A_{538}/A_{480} - A_{600}) \times DF \times MW \times V \times 100}{\varepsilon \times l \times m} \tag{7}$$

Where, A_{538}, A_{480}, and A_{600} are the absorbance of diluted extract at 480, 538, and 600 nm, respectively. *DF* is the dilution factor, and *l* is the path length (1 cm) of the cuvette; *V* is the volume of extract, L; *m* is the mass of beetroot powder, g. The molecular weights (*MW*) and molar extinction coefficients (ε) of betanin (*MW*=550 g/mol; ε=60000 L/(mol cm) in H_2O; λ=538 nm) and indicaxanthin (*MW*=308 g/mol; ε=48000 L/(mol cm) in H_2O; λ=480 nm) were used to quantify contents of betacyanin and betaxanthin, respectively.

Ascorbic acid content

The ascorbic acid content was determined using a ascorbic acid determination kit (Nanjing Jiancheng Institute of Bioengineering, Nanjing, China). Results were expressed as milligrams per one hundred grams of dry matter (mg/100 g dm). Ascorbic acid content was determined in three parallels.

Total phenolic content

The total phenolic content (TPC) was determined according to the Folin-Ciocalteu method described by Alvarez-Parrilla et al.[37] with minor modifications. In short, the diluted extract (0.5 mL) was blended with 2.5 mL of Folin-Ciocalteu reagent (10 %, v/v). After 3 min, 2 mL of sodium carbonate (7.5 %, w/v) was added. The mixture was incubated at 50 °C for 15 min and then cooled to room temperature. The absorbance was read at 760 nm with a spectrophotometer. A calibration curve using gallic acid was prepared between 20-100 mg/L. Results for TPC were calculated as milligrams gallic acid equivalents (GAE) per gram of dry matter (mg GAE/g dm).

Total flavonoid content

The total flavonoid content was measured according to the method of Souza et al.[38] with slight modifications. First, 5 mL of diluted extract was mixed with 0.3 mL of 5 % $NaNO_2$ solution (w/v) before standing for 5 min. Then, 0.3 mL of 10 % $AlCl_3$ solution (w/v) was added and stirred for 6 min. 0.4 mL of distilled water and 4 mL of 1.0 mol/L NaOH solution were added last. The mixture was left at room temperature for 15 min, and the absorbance was measured at 510 nm. A calibration curve using rutin was prepared between 200-1000 mg/L. Total flavonoid content (TFC) results were calculated in terms of milligrams rutin equivalents (RE) per gram of dry matter (mg RE/g dm).

Antioxidant capacity

Ferric reducing antioxidant power (FRAP) assay was detected according to the colorimetric method described by Benzie and Strain[39]. The FRAP solution was prepared by mixing 0.02 mol/L $FeCl_3$, 0.01 mol/L Tri-2-pyridyl-s-triazine (TPTZ) solution (prepared in 0.04 mol/L HCl solution) and 0.3 mol/L acetate buffer (pH 3.6) with the volumetric ratio of 1:1:10. Briefly, the FRAP solution (6 mL) and the extract (0.2 mL) were evenly blended and incubated at 37 °C for 10 min. Using anhydrous ethanol as the control, the mixture absorbance at 593 nm was recorded. All solutions were prepared on the same day of use.

The measurement method proposed by Re et al.[40] was used to determine the 2,2′-azino-bis- (3-ethylbenzthiazoline-6-sulfonic acid) (ABTS) radical scavenging ability of the extract. ABTS radical cation was generated by reacting the same volume of ABTS stock solution (7.00 mM) with 2.45 mM potassium persulphate and allowing the mixture to stand in dark for 12-16 h at room temperature. ABTS solution was diluted with anhydrous ethanol to achieve an absorbance of 0.700 ± 0.02 at 734 nm wavelength.

The antioxidant capacity was determined by establishing a standard curve using the scavenging capacity of trolox in various concentrations (0, 20, 40, 60, 80, 100 mg/L) against FRAP and ABTS radicals, and the results were expressed as milligrams trolox equivalents (TE) per gram of dry matter (mg TE/g dm).

Statistical analysis

All analyses were conducted in triplicates for each parallel of the pretreatments and drying trial. The experimental data were expressed as the mean ± standard deviation. One-way analysis of variance (ANOVA) was performed using SPSS Statistics Version 20 (IBM Corporation, Chicago, IL, USA) and significant differences among means were performed using Duncan's multiple range test at a significance level of $p < 0.05$ (95 % confidence intervals). Figures were drawn using Origin 2022 software (Origin Lab, Hampton, NH, USA).

Results and discussion

Drying time and final moisture content

In this study, the impacts of different pretreatments on the physicochemical properties of beetroot slices were examined by the way of steam blanching, freeze-thaw, ultrasound and osmotic dehydration prior to heat pump drying. The heat pump drying process for all trials was monitored and drying times for corresponding trials are given in Fig. 1. As can be seen, compared to CK, all pretreatments significantly improved drying efficiency and reduced drying time ($p < 0.05$). The drying time changed in the range of 215-331 min, and the beetroot slices subjected to FT showed the shortest dying time, while the CK recorded the longest drying time of 331 min. Beetroot slices subjected to FT, SB, OD, and US reached the heat pump drying endpoint rapidly, reducing the drying time by 35.1 %, 27.5 %, 26.1 %, and 17.8 %, respectively, compared to untreated samples. The beetroot slices carried to FT showed the lowest drying time of 215 min, with the highest drying rate. FT can be attributed to the pores that were formed in the internal region of the beetroot slices, which facilitated greater moisture migration due to the impact of crystallization[18]. This may be due to the formation of spaces in the tissue due to ice crystals that then facilitated water transfer during heat pump drying. This result is in consistent with the observation of Ando et al.[41] and Xu et al.[42]. Similar results were reported by Ai et al.[43] that FT pretreatment greatly altered water status and distribution of *Cistanche deserticola*, as well as significantly reduced drying time.

Lower moisture content is desirable quality for long-term storage of perishable food[44]. Moisture contents of fresh and dried beetroot slices were measured. Initial moisture content of fresh beetroot slices was found to be 85.21 % (w.b.). It can be seen from Fig. 1 that final moisture contents of heat pump dried beetroot slices ranged from 6.43 % (w.b.) to 7.36 % (w.b.), which did not differ significantly ($p >$ 0.05).

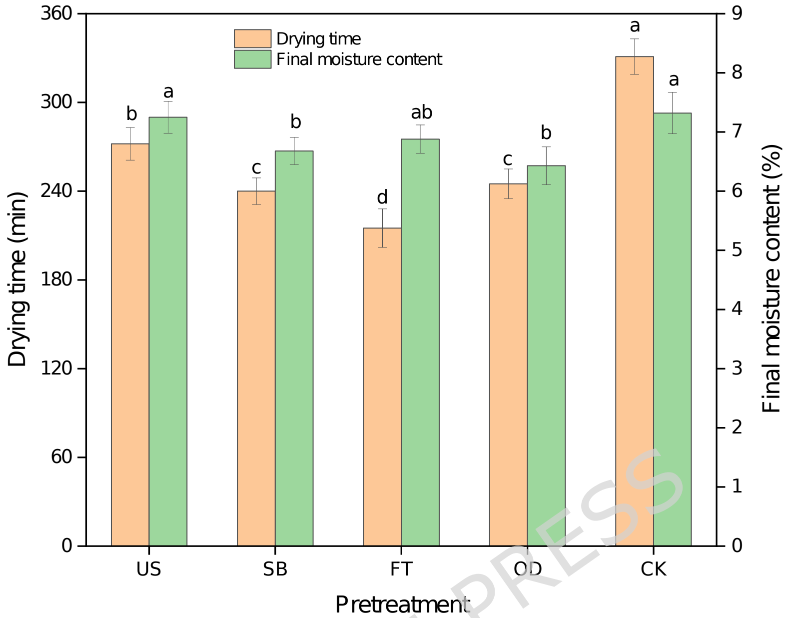

Fig. 1. Drying time and final moisture content of drying experiments for different pretreatments. CK-control, US-ultrasound, SB-steam blanching, FT-freeze-thaw, OD-osmotic dehydration. Different letters indicate statistically significant differences determined by Duncan's multiple range test ($p < 0.05$).

Rehydration ratio and hardness

The rehydration ratio indicates the water absorption capability of the dried product, which mainly depends on the pore size distribution of the microstructure[45]. Rehydration ratio can reveal cell structure damage, physical and chemical changes, as well as the product's ability to recover after pretreatment and drying[46]. The rehydration ratio and hardness of dried beetroot slices carried to various pretreatments are plotted in Fig. 2.

The pretreatment process typically causes irreversible changes in the sample's structure and limits its return to its original shape. As shown in Fig. 2, the rehydration ratio of dried beetroot slices subjected to different pretreatments showed significant differences compared to untreated samples ($p < 0.05$). The rehydration ratio of dried beetroot slices subjected to FT, US and SB remarkably improved in comparison with CK, while OD significantly decreased the rehydration ratio dried beetroot slices ($p < 0.05$). FT led to the highest rehydration ratio of 7.31 in dried beetroot slices, indicating that the freeze-thaw process caused minimal damage to the structure of beetroot slices. The formation of ice crystals during FT disrupted the internal structure of the sample, creating a porous network structure that aided rehydration through the capillary effect[47]. Following US treatment, the rehydration ratio of dried beetroot slices increased, which can be attributed to the increase of porosity and the development of micropore channels during US pretreatment[48]. OD resulted in the lowest rehydration ratio, indicating that OD caused the most severe damage to the cell structure of dried beetroot slices. The possible reason is that the osmotic dehydration process destroyed the permeability of the cell membrane, leading to severe cell damage and reducing the rehydration ability after heat pump drying. In summary, FT, US and SB offered distinct advantages in enhancing the rehydration rate of dried samples, whereas OD did not have any discernible effects.

Texture helps people understand the sensory characteristics of food taste through mechanical analysis. Hardness is one of crucial quality attributes for dried products, which is influenced by microstructure and moisture content[49]. Differences in textural properties are often due to changes in cell walls and membranes caused by thermal or pressure effects. Hardness is a key parameter in assessing the quality of dry products, influencing both taste and overall acceptability[50]. Compared with CK, different pretreatments had significant effects on hardness of dried beetroot slices ($p < 0.05$), except for OD treatment. Reduction in hardness of pretreated-dried beetroot slices were in the order of SB (1574.9 g) > OD (932.3 g) > CK (890.6 g) > US (819.5 g) > FT (544.9 g). The dried beetroot slices pretreated by SB displayed the greatest hardness. SB remarkably increased the hardness of dried beetroot slices ($p < 0.05$). It was reported that blanching remarkably increased the hardness of infrared-dried shiitake mushroom slices[51]. This may be due to original tissue collapse and dense structure formation in the beetroot slices from steam blanching followed by heat pump drying (Fig. 4). US significantly reduced the hardness of dried beetroot slices, similar to the findings in convective dried *Stropharia rugosoannulata* slices[52] and convective dried pineapple slices[53]. The dried beetroot slices carried to FT showed the lowest hardness, which was caused by the ice crystals generated by freezing. Ice crystals can damage the cell walls and membranes, altering the expansion pressure within cells[54].

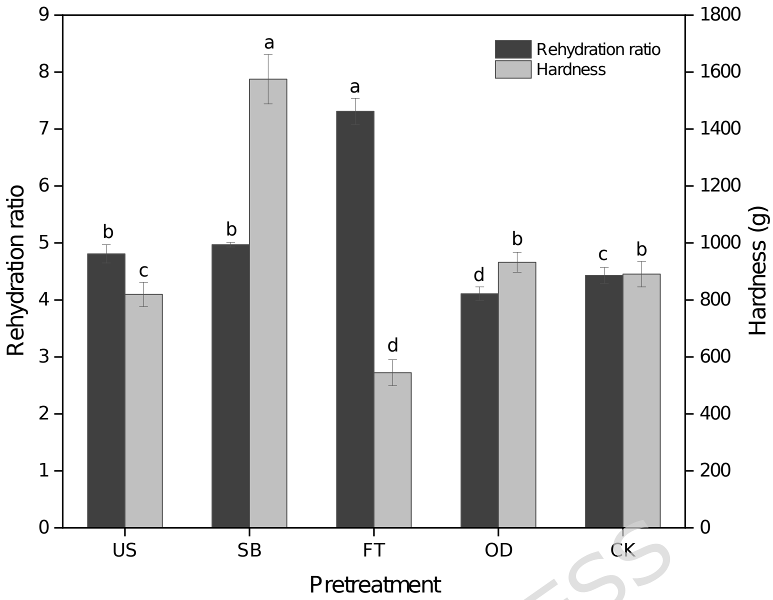

Fig. 2. Rehydration ratio and hardness of dried beetroot slices subjected to different pretreatments

Shrinkage rate and bulk density

The pretreatment typically causes irreversible changes in the sample's structure and limits its return to its original shape. The shrinkage rate and bulk density of the heat pump dried beetroot slices carried to different pretreatments are displayed in Fig. 3. The beetroot slices pretreated with steam blanching, freeze-thaw, ultrasound and osmotic dehydration might lead to more severe degree of cellular damage and higher extent of tissue shrinkage. Shrinkage rate was used to estimate the volume change of the dried beetroot slices in this study. As can be seen, the pretreatments resulted in the significant increase of shrinkage rate of dried beetroot slices ($p < 0.05$), which due to the internal tissue structure of the beetroot slices collapsed during various pretreatments, reducing internal gaps and increasing shrinkage[55]. The dried beetroot slices subjected to SB and US showed the maximum shrinkage rate (93.38 % and 93.17 %), and the differences between them were not significant ($p > 0.05$).

Bulk density plays a critical role in the packaging and transportation of fruit and vegetable powders, and a higher bulk density typically reduces the costs of packaging and transportation[56]. It was found that high shrinkage can lead to the improvement of the density and hardness of the litchis[57]. As illustrated in Fig. 3, pretreatments had a significant improvement in the bulk density of dried beetroot slices ($p < 0.05$). SB and OD resulted in the highest bulk density, namely 1.29 g/mL and 1.27 g/mL, respectively. The higher bulk densities in the dried beetroot slices indicate a more compact structure. It has been reported that structural deformation due to shrinkage and volume reduction results in density changes[58]. US produced the lowest bulk density (0.88 g/mL) among the four pretreatments, which perhaps due to the inverse correlation between porosity and bulk density[59], and US increased the porosity of beetroot slices. The application of pretreatments increased the bulk density of dried beetroot slices compared to CK. These findings indicate that pretreatment can increase the bulk density of beetroot slices, potentially enhancing its suitability for commercial packaging and transport. Similar findings were reported by Wan et al.[56] noting that the combination of cold plasma pretreatment with microwave coupled with pulsed vacuum drying resulted in the highest bulk density, and US-freeze drying yielded higher bulk density than that of freeze-dried samples without pretreatment. Similarly, Tajane et al.[60] reported that optimizing pretreatment and drying conditions is crucial for achieving the expected bulk density in neem fruit powder, supporting our observation in this study that bulk density can be effectively regulated by pretreatment methods.

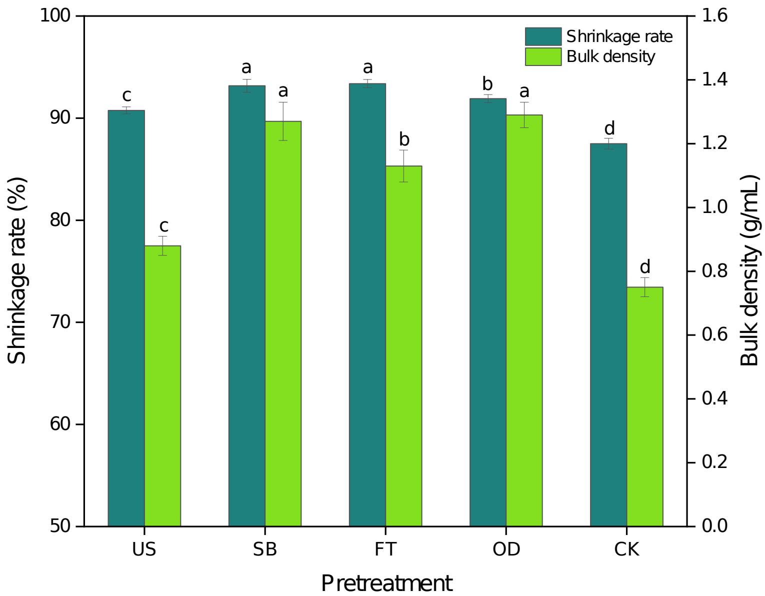

Fig. 3. Shrinkage rate and bulk density of dried beetroot slices subjected to different pretreatments

Color changes

Color can be said to be the first quality parameter that attracts consumers' attention to food products and hence is received critical attention during processing[61]. The effect of applied pretreatments on the color properties of heat pump dried beetroot slices was analyzed and results are given in Table 1. Color parameters of fresh beetroot slices were also measured and L^*, a^*, b^*, C and $H°$ values were found to be 27.73, 18.64, 2.39, 18.79 and 7.76, respectively. Generally, the color parameters of dried samples pretreated by different methods (SB, US, FT and OD) were significantly higher than the fresh sample ($p < 0.05$), except for b^* values. L^* values of the samples were examined. In general, a significant increase was observed in the L^* values of dried beetroot slices compared with that of fresh samples ($p < 0.05$). At this point, it is worth emphasizing that both pretreatment and drying process can lead to the presence of non-enzymatic browning reactions, which may result in changes in color parameters including brightness[62]. As seen in Table 1, the attribute a^* was significantly affected by pretreatments ($p < 0.05$), which caused the increase of redness compared to the fresh samples. Higher a^* values indicate the revelation of more red-pigmented compounds, such as betacyanin, which is very vital for human health. It was reported by Ochoa-Martinez et al.[63] that thermal treatment causes some degradation in red-orange betanins, increasing the values of a^*. US resulted in the highest a^* value, followed by OD and SB. No significant differences were observed between the a^* values of FT pretreated beetroot slices and untreated beetroot slices ($p > 0.05$).

Irrespective of whether pretreatment was applied or not, the C values of the dried beetroot slices significantly increased compared to the fresh sample ($p < 0.05$). The increase in C value is thought to be caused by the transformation of the color pigments with the influence of pretreatments and heat pump drying. As displayed in Table 1, significant differences were observed in $H°$ values between dried beetroot slices and fresh samples ($p < 0.05$). The $H°$ values of fresh and dried beetroot slices ranged from 7.76 to 58.62. When the results were examined, it was seen that regardless of the processes used, the *H*° values of the dried beetroot slices were significantly higher than the fresh sample ($p < 0.05$). Dried beetroot slices operated to FT showed the highest *H°* value, while SB led to the lowest *H°* value in comparison with those of the dried beetroot slices.

As is well known, the minimum change in color parameters compared to the fresh sample is an ideal quality criterion in drying process. The ΔE results of dried samples based on the fresh sample are illustrated in Table 1. In the case of this study, it was detected that there were some significant changes in ΔE values depending on pretreatments. The ΔE values of dried beetroot slices compared to fresh samples ranged from 13.27 to 21.37. This indicates that the beetroot slices displayed a visible browning phenomenon discernible to the naked eye after the drying process. In other words, the ΔE values in the dried beetroot slices carried to different pretreatments were remarkable and identifiable. The reason for this change may be attributed to the influence of various pretreatments and heat pump drying processes on color pigments, leading to their leaching, transformation or browning reactions[62]. The FT dried beetroot slices showed the least ΔE value, which indicated a better retention capability of color. The ΔE value of dried beetroot slices pretreated by OD were highest among all treatments, significant color change occurred. This could be explained by the rupture of beetroot cells after OD, the pigments flowed out with water and entered into the osmotic solution, resulting in the greatest color difference.

Table 1. The color properties of beetroot slices treated by the combination of pretreatment and heat pump drying

Pretreatment	*L**	*a**	*b**	*C*	*H*°	ΔE
US	42.59 ± 0.98^b	31.36 ± 0.95^a	1.83 ± 0.12^b	31.41 ± 0.95^a	17.15 ± 0.80^d	19.60 ± 0.63^b
SB	39.04 ± 1.03^d	27.76 ± 0.65^c	2.29 ± 0.21^a	27.85 ± 0.66^c	12.15 ± 0.87^e	14.56 ± 0.76^c
FT	39.77 ± 0.99^d	23.79 ± 0.53^d	0.41 ± 0.02^e	23.80 ± 0.53^d	58.62 ± 1.45^a	13.27 ± 0.81^d
OD	45.79 ± 1.04^a	29.91 ± 0.97^b	0.91 ± 0.06^c	29.92 ± 0.97^b	32.78 ± 1.22^c	21.37 ± 0.49^a
CK	41.11 ±	23.76 ± 0.95^d	0.68 ±	23.77 ±	35.12 ±	14.45 ±

	0.84^{c}		0.05^{d}	0.95^{d}	1.06^{b}	0.92^{c}
Fresh sample	27.73 ± 0.68^{e}	18.64 ± 0.38^{e}	2.39 ± 0.13^{a}	18.79 ± 0.39^{e}	7.76 ± 0.41^{f}	—

Note: Each value is expressed as the mean value ± standard deviation (n=8) different letters in the same row represent significant differences ($p < 0.05$) according to the Duncan's multiple range test.

The a* value is the foremost reference indicators for beetroot slices, and the a* value (a*=31.36) of the US pretreated beetroot slices was the highest, followed by OD pretreated beetroot slices and SB pretreated beetroot slices. This indicates that the beetroot cell fluid and betacyanins were destroyed in the pretreatment procedure, and they were unleashed into the cell space, which showed a stronger red color in dried beetroot slices. In summary, US had the potential to produce ruddy and attractive dried beetroot slices.

Microstructure analysis

The images of SEM of the dried beetroot slices preformed to different pretreatments and heat pump drying are presented in Fig. 4, which showed that different pretreatments had a notable impact on the microstructural changes of beetroot slices dried by heat pump. The cell structure of dried beetroot slices treated with US appeared relatively intact without significant shrinkage, which found is consistent with the US treated with okra[42]. This was attributed to the minor tissue damage caused by ultrasound treatment on beetroot slices. It possibly because that the formation of micro-spaces after US contributed to much more numbers of pathways for water diffusion, thus leading to faster water transfer during heat pump drying[64]. The cell walls of the dried beetroot slices pretreated with SB were severely destroyed, and only a partial cytoskeleton remained. Therefore, the surface of the beetroot slices became smooth and compact, and the tissue severely collapsed and contracted, stacking into a relatively dense structure. Similar result was also observed by Sun et al.[65]. As shown in Fig. 4, freezing the beetroot slices, followed by thawing, destroyed the cell's internal structure. FT caused damage to the integrity of the cell wall in beetroot slices, leading to partial collapse of the cells. the cell membrane was affected by the growth of ice crystals, causing the appearance of the micropores, cell membrane rupture, thereby promoting water transfer[66]. Compared to CK, the dried beetroot slices subjected to OD showed more seriously cell congregation and tissue shrinkage, along with the presence of cell collapse. This could be attributed to the infiltration of sucrose solution into the beetroot tissues, leading to cell rupture. It is noteworthy that SB induced severe cell collapse and tissue shrinkage, more tough surface and less pores were observed after heat pump drying. Thus, the application of US prior to heat pump drying significantly contributed to preserving the original structure of beetroot slices. This result is in line with the observation of Llavata et al.[67], who found that ultrasound could help to preserve the original structure of orange peel.

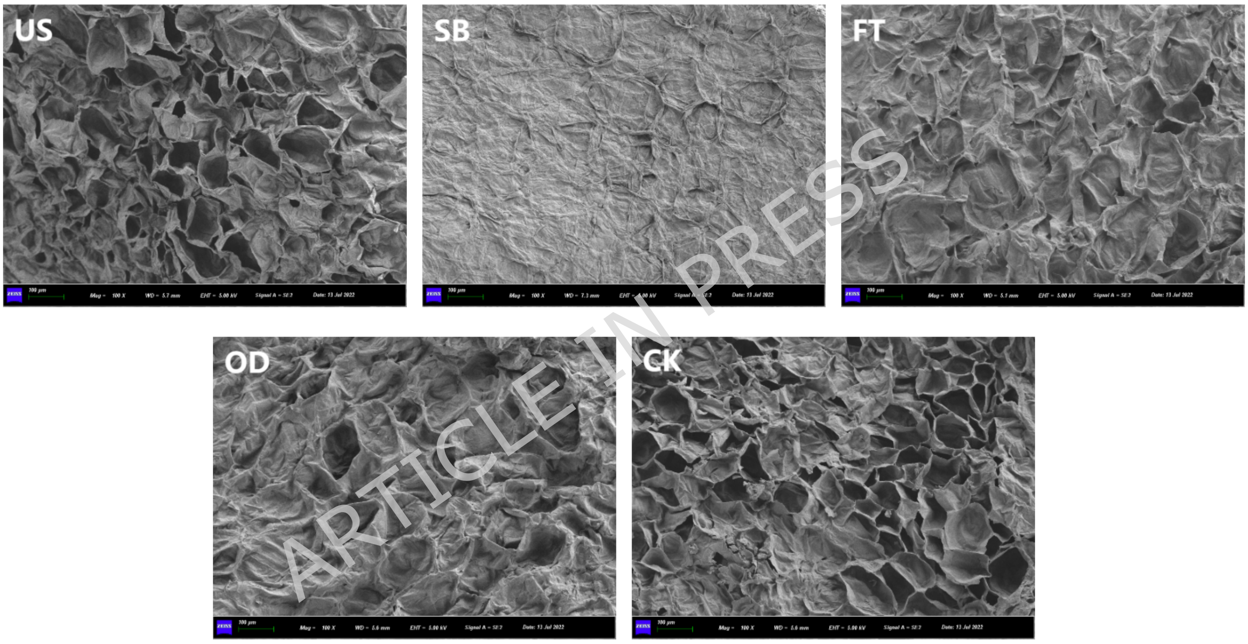

Fig. 4. The microstructure of the dried beetroot slices carried to different pretreatments combined with heat pump drying made using SEM (magnification 100×)

Betalain content

Betalains are the most abundant pigments present in beetroots that impart its characteristic color. Therefore, it is crucial to retain the amount of betalains for preserving better beetroot appearance, leading to higher consumer acceptability. Betalains are divided into betacyanins (red pigment) and betaxanthins (yellow pigment), according to their chemical structures and compositions[6]. The betalain content of dried beetroot slices subjected to different pretreatments are depicted in Fig. 5.

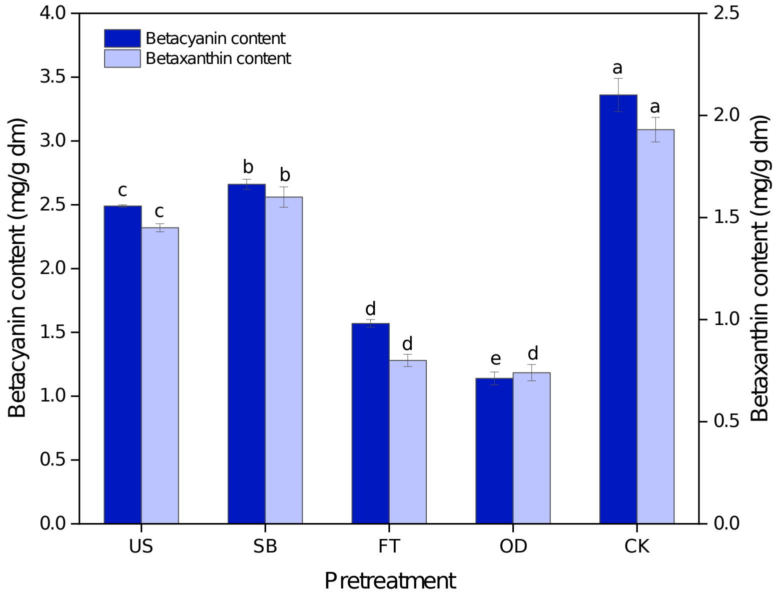

Fig. 5. Betalain content of dried beetroot slices under different pretreatments

Contents of betacyanin and betaxanthin of the CK were 3.36 mg/g dm and 1.93 mg/g dm, respectively, which were significantly higher than those of dried beetroot slices pretreated by various pretreatments ($p < 0.05$). This indicated that pretreatments could lead to partial loss of betalains. As expected, it can be noticed that SB resulted in higher betalain preservation than other pretreatments. OD led to the lowest contents of betacyanin and betaxanthin. A higher pigment loss could be mainly because of water-soluble pigments dissolved into permeation solution during OD treatment.

Ascorbic acid content

Fig. 6 illustrates the influence of different pretreatments on the ascorbic acid content of heat pump dried beetroot slices. Significant differences were observed in the ascorbic acid content of the different pretreated beetroot slices after heat pump drying ($p < 0.05$), and all the pretreatments yielded higher ascorbic acid content in comparison to CK. The heat pump dried beetroot slices without any pretreatment showed the lowest ascorbic acid content of 174.96 mg/100 g dm. Ascorbic acid is a heat-sensitive compound, and irreversible oxidation and thermal degradation occurred during heat pump drying. Meanwhile, the prolonged drying time aggravated the degradation of ascorbic acid, resulting in its loss. SB resulted in the highest ascorbic acid content of 342.28 mg/100 g dm, and the increase rate of ascorbic acid content reached 95.63 % in comparison with that of CK. Similar result was found by Sun et al.[65]. The possible reason is that steam blanching can improve extractability of ascorbic acid by destroying cell structure and decreasing the degradation during drying by shortening drying time[68].

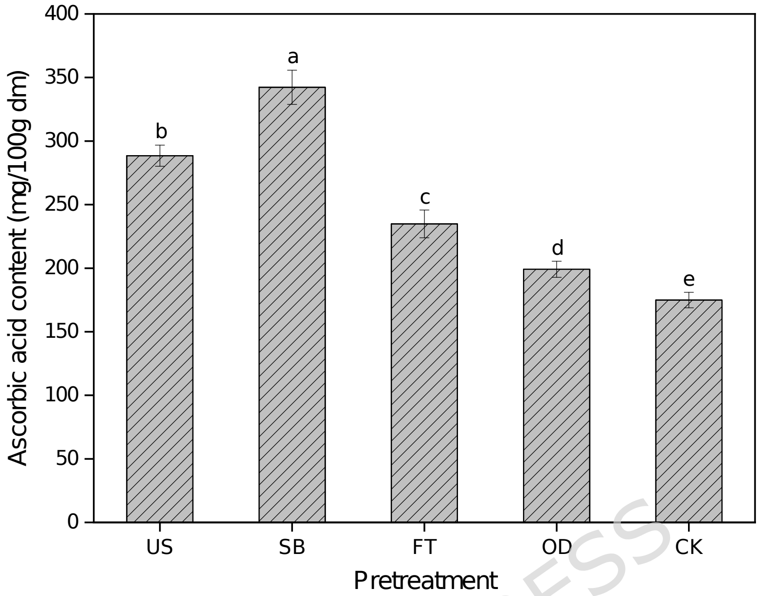

Fig. 6. Ascorbic acid content of dried beetroot slices subjected to different pretreatments

Total phenolic content and total flavonoid content

The total phenolic content (TPC) and total flavonoid content (TFC) in dried beetroot slices considering the different pretreatments are depicted in Fig. 7. The results showed that different pretreatment methods had a significant effect on the TPC of dried beetroot slices ($p < 0.05$). Higher TPC is usually desirable in food products due to their innate antioxidant potential, which can help scavenge free radicals formed in the human body. The US and SB pretreated beetroot slices had significantly higher TPC values in comparison with CK ($p < 0.05$). Surprisingly, the difference in TPC between the US and SB groups was not significant ($p > 0.05$). Although the drying time of SB group was shorter than that of US group, the cavitation effect of ultrasound led to easy extraction of phenolic compounds or inactivation of phenolic degrading enzymes[69]. Therefore, the use of ultrasonic before the drying process is conducive to the retention of bioactive compounds. US significantly increased the TPC of dried beetroot slices. This is in agreement with the observation of Fikry et al.[70] and Wang et al.[71]. Meanwhile, this phenomenon might be because SB can improve extractability of TPC by destroying cell structure and decreasing the degradation during drying by shortening drying time. In short, US and SB were efficiently retained the phenolic content, while OD and FT followed by heat pump drying significantly reduced the TPC as compared to CK ($p < 0.05$). The lower TPC contents of dried beetroot slices subjected to FT and OD were possibly due to the cellular damage that occurs during crystallization and dehydration, which sped up the release of phenolic compounds during pretreatments, thereby reducing the contents of TPC in the dried beetroot slices.

In the case of TFC, all pretreatments were significantly lower than that of the CK ($p < 0.05$), indicating all pretreatments exhibited adverse impacts on the retention of TFC. The TFC of dried beetroot slices after pretreatments were varied from 6.14 to 9.14 g RE/g dm. FT led to the lowest TFC, with a loss rate of up to 42.62 % compared to CK. The loss rate of TFC caused by SB was the lowest of 10.56 % in comparison with CK. It was found that FT and FT-US have a positive effect on the retention of flavonoids in vacuum freeze-dried apricots, while US has a negative impact on the retention of flavonoids[47]. In summary, SB is an ideal pretreatment for preserving TPC and TFC.

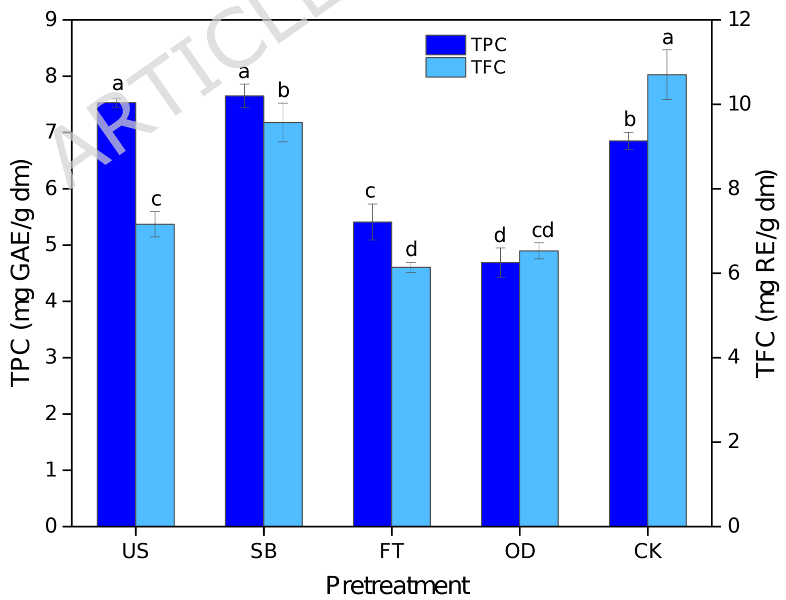

Fig. 7. TPC and TFC of dried beetroot slices subjected to different pretreatments

Antioxidant capacity

Due to its high content of betalains, phenolic acids, ascorbic acids, flavonoids, vitamin B, and other substances, beetroots exhibit strong antioxidant capacity[1]. As a consequence, antioxidant capacity is also one of the key quality evaluation indicators of beetroots. In this study, antioxidant capacity of dried beetroot slices was determined by FRAP and ABTS assays. The antioxidant capacity results are illustrated in Fig. 8. The results showed that different pretreatment methods significantly affected the FRAP value and ABTS free radical scavenging capacity of dried beetroot slices ($p < 0.05$). Concerning FRAP values, there were significant distinctions observed in dried beetroot slices among various pretreatments ($p < 0.05$). The FRAP values of SB, US, FT, and OD pretreated beetroot slices were reduced by 13.38 %, 27.31 %, 36.89 %, and 43.76 % compared to CK (11.06 mg TE/g dm), respectively.

As for the ABTS radical scavenging activity, significant impacts were observed in dried beetroot slices among different pretreatments, except for SB. As can be depicted in Fig. 8, there was no significant difference between SB beetroot slices and unpretreated beetroot slices ($p > 0.05$), while the lowest ABTS value was detected in dried beetroot slices pretreated with OD before heat pump drying. The ABTS values of dried beetroot slices pretreated by OD, FT, and US was 27.00 %, 22.77 %, and 12.41 % lower than that of the untreated beetroot slices, respectively. Vallespir et al.[72] found that FRAP and ABTS values of the pre-frozen beetroots significantly decreased in comparison with those of the unpretreated-beetroots ($p < 0.05$). According to previous studies, US can improve antioxidant capacity of fruits and vegetables. It was found that ultrasound pretreatment enhanced antioxidant activity of vacuum freeze-dried okra[42]. Generally speaking, the antioxidant capacities of dried beetroot result from the joint action of betalains, ascorbic acids, total phenols and flavonoids. The loss of antioxidant capacity is attributed to the loss of antioxidants during the pretreatments, and the cell structural changes that promote oxidation due to the air exposure during the drying process[72]. However, the reduction of antioxidant capacity still allowed for good retention of ascorbic acid in all beetroot slices. In conclusion, the antioxidant capacity of the pretreated beetroot slices was observed to be weaker than CK, and SB showed higher retention in antioxidant capacity of dried beetroot slices than other preteatments.

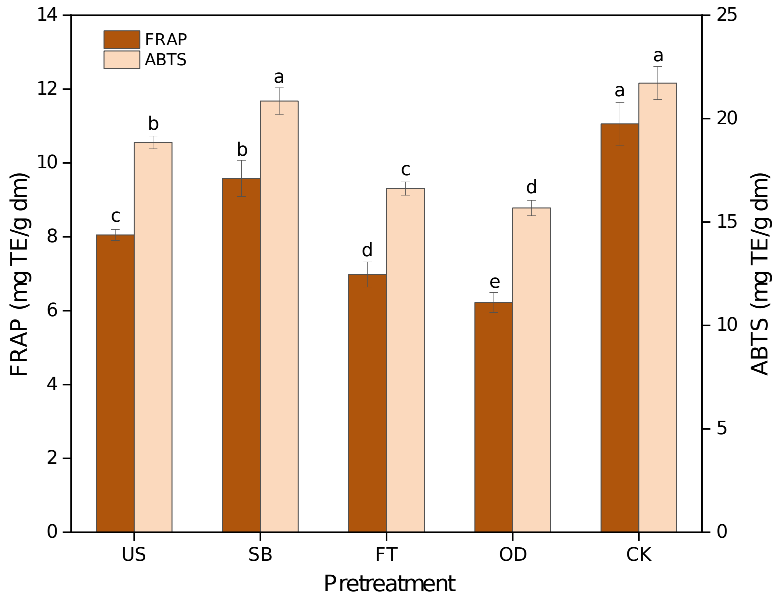

Fig. 8. FRAP and ABTS values of dried beetroot slices subjected to different pretreatments

Conclusion

The effects of US, SB, FT, and OD pretreatment on drying time, physicochemical properties, phytochemical compounds, and antioxidant capacity of heat pump dried beetroot slices were investigated. The results demonstrated that FT significantly reduced the drying time, and decreased drying time by 35.1 % compared to the CK. Meanwhile, FT led to the highest rehydration ratio of 7.31 in dried beetroot slices. Color analysis showed that US pretreated beetroot slices exhibited a more attractive red color with a^* value of 31.36. Microstructure analysis revealed that the application of US before heat pump drying could better preserve the structure of beetroot slices. SB induced severe cell collapse and tissue shrinkage of beetroot slices, resulted in higher hardness, shrinkage rate, and bulk density than other pretreatments. In terms of phytochemical compounds, beetroot slices subjected to SB exhibited a higher retention of betacyanin, betaxanthin, TPC, and TFC in comparison with those of US, FT, and OD. Furthermore, SB resulted in the highest ascorbic acid content of 342.28 mg/100g dm, and its increase rate reached 95.63 % compared with CK. As for antioxidant capacity, SB displayed higher retention of FRAP value and ABTS radical scavenging activity compared to other pretreatments. Based on the above results, it can be concluded that the appropriate selection of pretreatment can remarkably enhance the quality properties of beetroot slices, and SB is a promising pretreatment prior to heat pump drying for beetroot slices. Therefore, further research is highly recommended to fully explore the potential of combination SB with other pretreatment techniques to improve the large-scale production of high-quality dried beetroot slices.

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Author Contribution

Yan Liu designed the research, analyzed data, and wrote the manuscript draft. **Xiaoxian Tang** conducted the experiments, analyzed data, and revised the manuscript. **Chuan Li** and **Dingjin Li** participated in analyzing the results and revising the manuscript. **Dan Gao** participated in data collection and analysis. **Aiqing Ren** and **Zhenhua Duan** provided funding, supervision, and revision.

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Data Availability

Data will be made available on request. Please contact the author (Yan Liu), E-mail: liuyan130832@126.com.

Declarations

Ethical Approval Not applicable.

Competing Interests The authors declare no competing interests.

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