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Cactus polysaccharides enhance preservative effects of ultrasound treatment on fresh-cut potatoes☆

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ABSTRACT

The shelf life of fresh-cut fruits and vegetables is affected by microbial growth, enzymatic browning, and loss of flavor. Although ultrasound (US) treatment is often used in the preservation of fresh-cut fruits and vegetables, it has limited antibacterial and preservative effects. Here, we used cactus polysaccharides (CP) to enhance the preservative effect of ultrasound treatment and extended the shelf life of fresh-cut potatoes. The results showed that combined treatment (CP + US) exerted better antimicrobial and anti-browning effects than individual treatments (either US or CP alone). In addition, CP + US has no adverse effect on texture and quality properties, as well as reduced the mobility of internal water. Combination treatment not only significantly decreased the activities of polyphenol oxidase and peroxidase ($P < 0.05$), but also maintained a high level of phenylalanine ammonia lyase activity and total phenol content during storage. It also maintained the integrity of cell membrane and reduced its permeability by inhibiting the peroxidation of membrane lipids. In addition, CP + US treatment significantly inhibited the activity of antioxidant enzymes and maintained a high DPPH scavenging ability. GC-IMS technology was used to evaluate the flavor of fresh-cut potatoes. The results showed that CP + US treatment reduced the production of a peculiar smell during storage and maintained a good flavor by inhibiting the production of aldehydes. Taken together, these results indicate that the effective preservation method of CP + US treatment can be utilized to increase the shelf life of fresh-cut potatoes.

1. Introduction

In recent years, global economic prosperity has increased consumer demand for convenience foods, leading to the rapid development of fresh-cut fruit and vegetable industry [1]. Potatoes, one of the most important fresh-cut agricultural products, are rich in carbohydrates, proteins, vitamin C, trace elements, and amino acids, and are commonly used in homes and catering industry [2]. However, the washing, peeling, and cutting of potatoes can lead to enzymatic browning, soft texture, flavor loss, and microbial spoilage, all of which lower the potential economic value of fresh-cut potatoes [3,4]. Therefore, it is important to prevent browning while maintaining the flavor of fresh potatoes and prolonging the shelf-life.

Ultrasound treatment is a safe, environmentally friendly, and non-thermal technology used in the processing and preservation of fruits and vegetables to inhibit the growth of microorganisms and enzymatic browning [5,6]. The ultrasonic treatment produces locally high temperature and pressure generated by the ultrasonic "cavitation" effect. The cavitation effect thereby damages the cell walls and membranes of plant cells and microorganisms, hence the free radicals generated by ultrasonic water splitting interact with the amino acid residues, leading to sterilization and browning inhibition [7]. Ultrasound treatment improves the sensory quality of fresh-cut apples [8], strawberries [9], kiwifruit [10], and lettuce [11], and control the enzymatic browning of related products. However, ultrasound treatment alone has limited antibacterial and preservative effects [1]. In fresh-cut yellow melons,

☆ Abbreviations: ultrasound (US); cactus polysaccharides (CP); colony-forming units (CFU); polyphenol oxidase (PPO); phenylalanine ammonia lyase (PAL); gas chromatography–ion mobility spectrometry (GC–IMS); control (CK).

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the number of mesophilic aerobic bacteria has been reported to decrease from 2.9 log colony-forming units (CFU)/g to 2.8 log CFU/g following ultrasound treatment alone, and to 2.5 log CFU/g following combined treatment with ultrasound and sodium hypochlorite (NaOCl) [12]. In Chinese cabbage, ultrasound + NAOCl combined treatmen showed better antibacterial effects than ultrasound treatment alone, without any adverse effects on the leaves [13]. Meanwhile, the application of chemical additives in foods remains controversial and has low acceptance among consumers. Therefore, safe and natural substances that can enhance the preservative effects of ultrasound remain warranted.

Edible coatings made of natural polysaccharides are non-toxic, leave no chemical residues, and have antibacterial properties , hence are used to delay quality deterioration in fresh-cut fruits and vegetables [14,15]. Cactus is a natural source of polysaccharides and grows in various climatic conditions, especially in arid climates such as the Mediterranean and Central America [16]. Cactus polysaccharides exhibit various biological activities, including antioxidant and bacteriostatic, antidiabetic, immunostimulatory, antitumor, and neuroprotective [17,18]. For example, an edible coating based on *Opuntia dillenii* polysaccharides (ODP) inhibits enzymatic browning and microbial development in fresh-cut potatoes [18]. Polysaccharide films on the surfaces of fresh-cut fruits and vegetables prolong the shelf-life and reduce the loss of flavor by limiting water transfer and air permeability [19]. Therefore, cactus polysaccharides (CP) are promising natural additives with potential application in the preservation industry.

In this study, we evaluated the preservative effects of ultrasound treatment (alone and in combination with CP) on fresh-cut potatoes. We first explored the inhibitory effect of combined and single treatments on microorganisms, and investigated the the texture and quality parameters. Then, the alterations in browning and enzymes associated with browning, such as polyphenol oxidase (PPO), peroxidase (POD), and phenylalanine ammonia lyase (PAL) was analyzed. In addition, the effects of these treatments on cell membrane permeability, lipid peroxidation, and antioxidant capacity were determined. To elucidate the association between potato spoilage and flavor compounds, gas chromatography–ion mobility spectrometry (GC-IMS) was used to analyze volatile flavor compounds in stored samples subjected to different treatments. Our results provide new insights into the extension of the fresh-cut potato shelf-life and development of novel fresh-cut fruit and vegetable preservation strategies.

2. Materials and methods

2.1. Materials and sample preparation

Potatoes (B5141-6) were purchased from a farm market in Zhang Jiakou, China, and stored at 4 °C. We ensured that the potatoes had no mechanical damage and were similar in size and ripening stage. CP (water extract; extraction ratio, 10:1; 50 %) were obtained from Lanzhou Senyuan Biological Co., ltd. (China).

Prior to experimentation, all utensils were sterilized with 75 % ethanol; the potatoes were rinsed with tap water. Slices of selected potatoes, each 5-mm thick, were randomly separated into four groups, each receiving a different treatment: control (CK), CP, US, and CP + US. In the CK group, the potato slices were immediately immersed in distilled water for 10 min. Meanwhile, the remaining groups were treated as follows: CP (1 %, w/w; 10 min); US (KQ-1018, Dongguan, China; 40 kHz, 480 W, 10 min); CP + US (CP: 1 %, w/w; US: 40 kHz, 480 W, 10 min). The potatoes (g) were treated with the respective solutions (mL) at a ratio of 1:4. At the end of the treatment, all samples were wiped with gauze, transferred to a biological safety cabinet to dry for 1 min, put in a storage box (240 mm × 160 mm × 40 mm), and stored at 4 °C for 8 d. The samples were tested every 2 d.

2.2. Microbiological assay

The total number of microbial colonies, mold, and yeast in the control and experimental groups were determined as previously described [20]. First, a 25 g sample was mixed with 225 mL normal saline solution to fully homogenize. A 1:10 sample homogenate was prepared. Then, a 10-fold increasing series of sample homogenates was made; 1 mL of the serial dilutions was added to Petri dishes and mixed with 20 mL of different selective agars. To measure the total number of colonies, the plates were inverted and incubated at 37 °C for 48 h once the agar was solidified. To measure mold and yeast, the plates were incubated at 28 °C for 96 h.

2.3. Color evaluation

Using a colorimeter, color variations in fresh-cut potato slices were recorded (CR-400, Konica Minolta, Japan). The colorimeter was initially calibrated with a white calibration plate to test the samples under each treatment. Each sample was measured three times and the average was calculated and recorded. The values were expressed as total color difference (ΔE) and were calculated as follows [21]:

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} \Delta b^{*2}}$$

2.4. Texture analysis

The firmness, brittleness, and chewiness were determined using a texture analyzer (TMS-Pro, USA). Texture analysis of potatoes was conducted using a cylindrical probe P/5 with a diameter of 5 mm. The test parameters were as follows: the speed before the test, test speed, and upward speed after the test were 1 mm/s, compression deformation was 50 %, and the pause time between compressions was 5 s. Each sample was measured 10 times in parallel, and the results were averaged.

2.5. Soluble solids, pH and cooking loss

The fresh-cut potatoes were homogenized and the supernatant was collected via centrifugation. Soluble solids were measured with a digital sugar meter (PAL-1, ATAGO, Japan), while the pH was measured with a pH meter (PHS-3E, China). All samples were assayed in triplicate.

The fresh-cut potatoes were boiled for 10 min and drained, weighed as M_1, while unboiled samples as M_0. Each measurement was repeated three times, and cooking loss rate was calculated as follows:

$$Cooking\ loss\ (\%) = M_0 - M_1/M_0$$

2.6. Water status and distribution

The water state and distribution of fresh-cut potatoes were measured using low field nuclear magnetic resonance (LF NMR) analyzer (Niumag Electric Corporation, China). Approximately 10 g samples were used for each test. Carr-Purcell-MeiboomGill (CPMG) pulse sequences were used to obtain decay signals. The main parameters of signal acquisition are as follows: time waiting (TW) = 3,000 ms; time echo (TE) = 1 ms; number echo (NECH) = 9,000, scanning times (ST) = 16.

2.7. Enzyme extractions and assays

PPO activity was determined as previously reported [22] with some modifications. Fresh-cut potatoes (5 g) were randomly sampled, mixed with 5 mL of the PPO extracting solution (1 % Triton X-100, 4 % polyvinylpyrrolidone, and 1 mmoL polyethylene glycol) in a pre-cooled mortar, and homogenized. The homogenates were crushed in an ice bath and centrifuged for 30 min at 4 °C and 12000 × *g*. The supernatant was used for the analysis of PPO and POD activity. A 100 μL aliquot of the supernatant was added to a solution consisting of 1 mL of 50 mmol/L

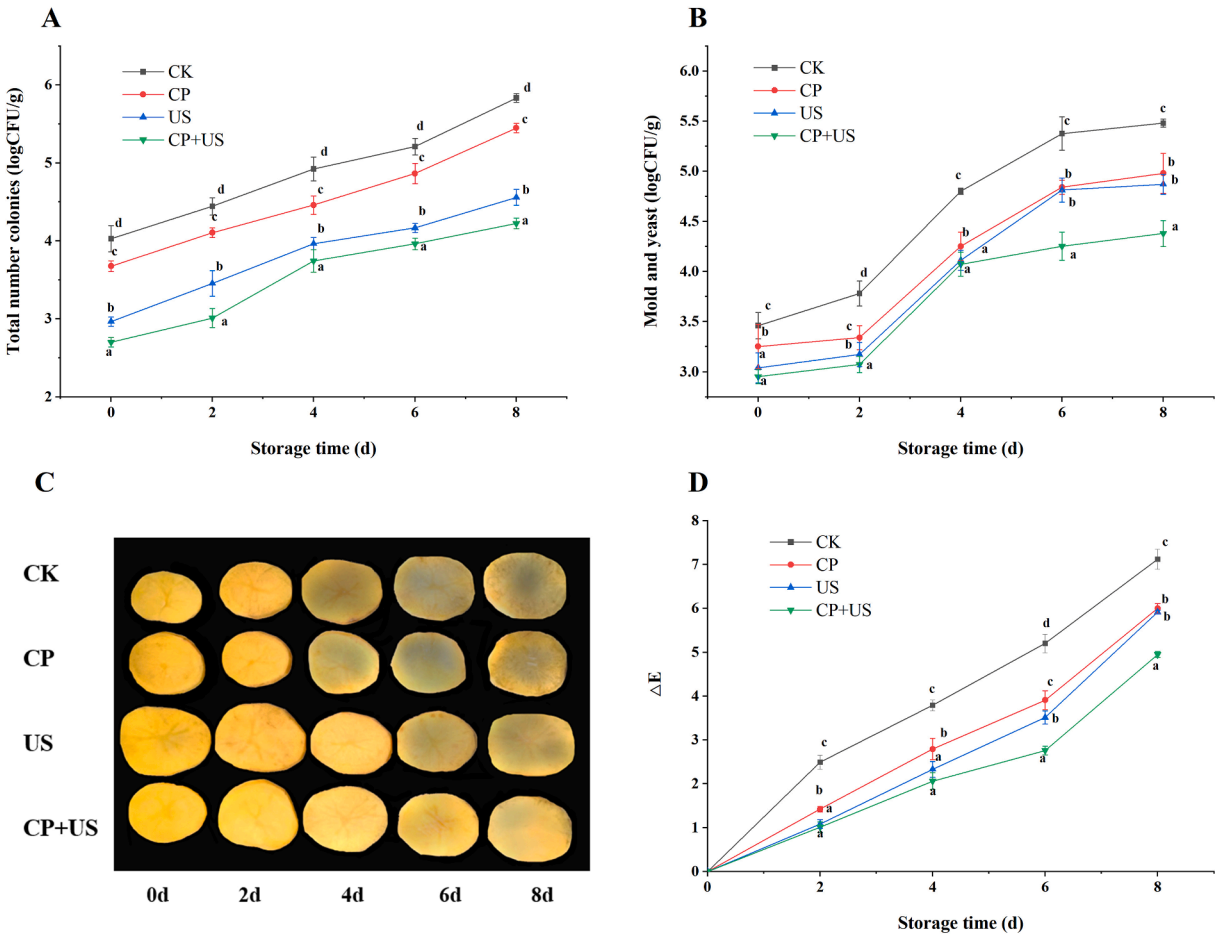

Fig. 1. Changes in the total number of colonies (A), mold and yeast (B), photographs (C), and total color difference (D) of fresh-cut potatoes under different treatments (CK, CP, US and CP + US) during storage at 4 °C for 8 days. Data are expressed as the mean ± standard deviation. Treatments at the same storage time are expressed by different letters showing significant differences ($P < 0.05$).

catechol solution and 4 mL of sodium acetate buffer solution (50 mmol/L, pH 5.5). The absorbance was measured at 420 nm.

POD activity was quantified as previously described [23], with some modifications. The POD extracting solution was obtained as described above. A total of 100 L of H_2O_2 (0.5 mol/L) was added after the supernatant (0.5 mL) was combined with 3 mL of guaiacol solution (25 mmoL/L). The absorbance was measured at 470 nm.

PAL activity was assayed according to the reported method [24]. Fresh-cut potatoes (2 mg) were mixed with 5 mL boric acid buffer (PVP at 40 g/L, EDTA at 2 mM, and b-mercaptoethanol at 5 mM) and ground in a pre-cooled mortar. The homogenized samples were centrifuged at 10000 × *g* at 4 °C for 30 min. Next, 0.5 mL of the supernatant mixture was rapidly added to 3 mL boric acid buffer (PH 8.8) and 0.5 mL of 20 mM L-phenylalanine and maintained at 37 °C for 10 min. The absorbance was measured at 290 nm. After incubating at 37 °C for 60 min, the absorbance at 290 nm was measured.

All enzyme activities were measured in U/g of fresh tissue weight.

2.8. Total phenolic content

Analysis of the total phenolic content was performed as previously described [25]. Fresh-cut potatoes (2 g) were added to 4 mL of 65 % acetone, homogenized, incubated at 25 °C for 3 h, and centrifuged at 10000 × *g* at 4 °C for 30 min. The supernatant solution was diluted to 0.4 mL and combined with 0.5 mL of the Folin-Phenol reagent before incubating for 10 min. After that, 0.5 mL of a 10 % Na_2CO_3 solution was added to the mixture along with 10 mL of distilled water. The sample was incubated in a water bath at 25 °C for 2 h and the total phenolic content was estimated using a gallic acid standard curve after the absorbance at 765 nm was measured.

2.9. Malondialdehyde content

Malondialdehyde (MDA) content was determined by a previous method with slight modification [17]. Approximately 1 g of fresh-cut potatoes were homogenized in 5 mL of a 100 g/L trichloroacetic acid solution before the homogenate was centrifuged at 10000 × *g* for 20 min at 4 °C. The mixture was combined with 2 mL of the supernatant and 2 mL of 0.67 % TBA, then heated for 20 min. The mixture was centrifuged as described above when it reached 25 °C. The MDA content is presented as mmol/kg of fresh weight, while absorbance was determined at 450, 532, and 600 nm.

2.10. Membrane permeability

A conductivity meter (DSS-307, China) was used to test the electrical conductivity, which correlates with membrane permeability [26]. The conductivity of the distilled water used in the experiment was measured as P_0. Using a hole punch with a diameter of 10 mm, potato tissue samples were taken and surface-dried with filter paper, rinsed three times with distilled water, and placed in a test tube. Approximately 20 mL of distilled water was added and incubated for 30 min. Initial conductivity (P_1) was measured with a conductivity meter. The test tube was placed in a boiling water bath for 15 min to kill the plant tissue. The

tissue's final conductivity (P_2) was assessed after cooling to 25 °C. Each measurement was repeated three times, and electrical conductivity was calculated as follows:

$$Electrical\ conductivity(\%) = (P_1 - -P_0)/(P_2 - - P_0)100.$$

2.11. Antioxidant capacity and catalase activity

Using a 2, 2-diphenyl-1-picrylhydrazyl (DPPH) radical-scavenging assay, the antioxidant capacity of fresh-cut potatoes was assessed (DPPH assay) [27]. Fresh-cut potatoes were ground and centrifuged at 10000 × *g* for 15 min at 4 °C. The supernatant was gathered and combined for a 30-min reaction with 4 mL of DPPH solution (257.7 mg/L) and 1 mL of 95 % ethanol. The absorbance was measured at 517 nm (A_0). After that, 1 mL of the supernatant was combined with 4 mL of 95 % (w/w) ethanol, and absorbance was determined at 517 nm (A_1). The absorbance of 4.0 mL of DPPH (257.7 mg/L) and 1.0 mL of supernatant was then measured at 517 nm (A_2). The antioxidant capacity of potato tissues was calculated as follows:

$$DPPH\ scavenging\ capacity(\%) = \{1 - [(A_0 - - Ai)/A0]\}100.$$

Catalase activity (CAT) was evaluated as previously described [28], with slight modifications. Approximately 5 g of fresh-cut potatoes were mixed with 10 mL of 0.1 M phosphate buffer (5 % polyvinyl pyrrolidone and 5 mmol/L dithiothreitol), homogenized in an ice bath, centrifuged at 12000 × *g* for 30 min at 4 °C, and then kept at 4 °C for future use·H_2O_2 solution (2.9 mL; 20 mmol/L) was added to 100 μL of the supernatant and absorbance was measured at 240 nm immediately. CAT activity was expressed as U/g of fresh weight.

2.12. Analysis of volatile organic compounds by HS-GC-IMS

An HS-GC-IMS taste analyzer (FlavourSpec®) from Gesellschaft für Analytische Sensorysteme mbH was used to quantify volatile chemicals (G.A.S., Dortmund, Germany). A headspace container was filled with precisely weighed (10 g) tissue samples. The following parameters were used for the GC-IMS experiment: analysis period of 30 min; column type of FS-SE-54-CB-1; column temperature of 60 °C; carrier gas/drift gas of high-purity nitrogen; detector temperature of 45 °C. Conditions for the headspace injection unit included the following: injection volume of 500 L; incubation period of 30 min; incubation temperature of 45 °C; injection needle temperature of 85 °C; incubation speed of 500 r/min; drift flow speed of 150 mL/min; carrier gas flow rate of 2–150 mL/min.

2.13. Statistical analysis

Three duplicates of each experiment were conducted. A one-way analysis of variance (ANOVA) analysis was conducted using In SPSS 18.0; all data were reported as the mean ± standard deviation. Duncan's multiple range test was used to compare sample mean differences; significance was set at $P < 0.05$. Data processing and analyses were completed with Origin 2019 software. The instrument's included LAV analysis program was used to examine volatile organic compounds. For qualitative analysis, the GC-IMS software's built-in NIST and IMS databases were used, and the Gallery plugin was employed to create chemical fingerprints.

3. Results and discussion

3.1. Effect of US combined with CP treatment on microbial growth

We evaluated the effects of the CP, US, and CP + US treatments on the total number colonies and amount of mold and yeast in fresh-cut potatoes (Fig. 1A, B). Compared with the CK group, significantly fewer microorganisms ($P < 0.05$) were observed in all remaining groups. It has been reported that 5.0 log CFU/g of total colonies of mold and yeast were used as the limit to ensure the microbial quality of fresh-cut fruits and vegetables [29]. The CP coating has a bacteriostatic effect and inhibits the growth of microorganisms on the surface of fresh-cut potatoes [18]. Accordingly, CP treatment alone significantly reduced the number of microorganisms in potato samples ($P < 0.05$; Fig. 1A, B). This treatment limited the total number of colonies to < 5.0 log CFU/g within 6 d while mold and yeast were controlled to acceptable limits within 8

Table 1
The influence of different treatments (CP, US and CP + US) on firmness, brittleness, chewiness, soluble solids, pH and cooking loss of fresh-cut potatoes.

	Different treatment	Storage time/d 0	2	4	6	8
Firmness/N	CK	89.52 ± 0.65^{a}	85.23 ± 2.15^{a}	78.60 ± 1.96^{a}	77.82 ± 1.84^{a}	70.37 ± 1.45^{a}
	CP	89.80 ± 1.37^{a}	85.96 ± 2.23^{a}	79.77 ± 0.56^{ab}	76.97 ± 2.70^{a}	71.12 ± 1.52^{ab}
	US	89.41 ± 2.03^{a}	87.16 ± 0.82^{a}	82.56 ± 1.28^{b}	80.78 ± 0.95^{ab}	75.15 ± 3.33^{ab}
	CP + US	89.98 ± 0.98^{a}	87.89 ± 1.70^{a}	82.71 ± 0.53^{b}	80.00 ± 0.96^{b}	75.52 ± 0.92^{b}
Brittleness/mm	CK	1.94 ± 0.03^{a}	1.91 ± 0.04^{a}	1.85 ± 0.01^{a}	1.80 ± 0.02^{a}	1.77 ± 0.01^{ab}
	CP	1.95 ± 0.02^{a}	1.90 ± 0.01^{a}	1.86 ± 0.03^{a}	1.81 ± 0.00^{a}	1.76 ± 0.02^{a}
	US	1.94 ± 0.03^{a}	1.94 ± 0.01^{a}	1.89 ± 0.00^{a}	1.87 ± 0.02^{a}	1.80 ± 0.01^{bc}
	CP + US	1.94 ± 0.02^{a}	1.94 ± 0.02^{a}	1.90 ± 0.02^{a}	1.89 ± 0.02^{a}	1.82 ± 0.01^{c}
Chewiness/mJ	CK	49.18 ± 1.11^{a}	47.99 ± 0.2^{a}	47.67 ± 0.36^{a}	46.05 ± 0.05^{a}	44.32 ± 0.35^{a}
	CP	49.72 ± 0.11^{a}	48.12 ± 0.38^{a}	48.01 ± 0.56^{ab}	47.23 ± 0.44^{a}	46.12 ± 0.63^{a}
	US	49.43 ± 0.37^{a}	48.93 ± 0.77^{a}	48.32 ± 0.30^{ab}	47.34 ± 0.45^{a}	46.45 ± 0.44^{ab}
	CP + US	49.33 ± 0.19^{a}	48.81 ± 0.11^{a}	48.90 ± 0.24^{b}	48.00 ± 0.25^{a}	47.03 ± 0.15^{b}
Soluble solids (%)	CK	4.94 ± 0.02^{a}	4.79 ± 0.05^{a}	4.69 ± 0.01^{a}	4.40 ± 0.04^{a}	4.26 ± 0.07^{a}
	CP	4.95 ± 0.02^{a}	4.81 ± 0.02^{a}	4.77 ± 0.02^{ab}	4.49 ± 0.02^{ab}	4.36 ± 0.02^{a}
	US	4.94 ± 0.01^{a}	4.84 ± 0.02^{a}	4.81 ± 0.02^{ab}	4.65 ± 0.02^{bc}	4.43 ± 0.03^{b}
	CP + US	4.94 ± 0.02^{a}	4.85 ± 0.02^{a}	4.8 ± 0.02^{b}	4.67 ± 0.02^{c}	4.45 ± 0.02^{c}
pH	CK	6.07 ± 0.01^{a}	5.95 ± 0.02^{a}	5.71 ± 0.03^{a}	5.50 ± 0.02^{a}	5.41 ± 0.01^{a}
	CP	6.10 ± 0.01^{a}	5.94 ± 0.02^{a}	5.74 ± 0.03^{b}	5.52 ± 0.02^{b}	5.40 ± 0.02^{b}
	US	6.12 ± 0.01^{a}	5.97 ± 0.01^{a}	5.76 ± 0.01^{b}	5.58 ± 0.03^{c}	5.49 ± 0.01^{b}
	CP + US	6.09 ± 0.01^{a}	5.97 ± 0.01^{a}	5.78 ± 0.02^{b}	5.62 ± 0.03^{c}	5.55 ± 0.02^{b}
Cooking loss (%)	CK	8.05 ± 0.01^{a}	8.12 ± 0.03^{a}	8.89 ± 0.02^{a}	9.45 ± 0.03^{a}	10.23 ± 0.01^{a}
	CP	8.04 ± 0.01^{a}	8.10 ± 0.02^{a}	8.85 ± 0.02^{ab}	9.41 ± 0.01^{ab}	10.19 ± 0.03^{ab}
	US	8.04 ± 0.02^{a}	8.07 ± 0.03^{a}	8.80 ± 0.03^{ab}	9.39 ± 0.02^{b}	10.18 ± 0.01^{b}
	CP + US	8.05 ± 0.01^{a}	8.01 ± 0.01^{a}	8.80 ± 0.02^{b}	9.40 ± 0.04^{ab}	10.18 ± 0.01^{ab}

Values are means ± standard deviation (n = 3). Different letters represent significant differences between different treatment groups at the same storage time ($P < 0.05$).

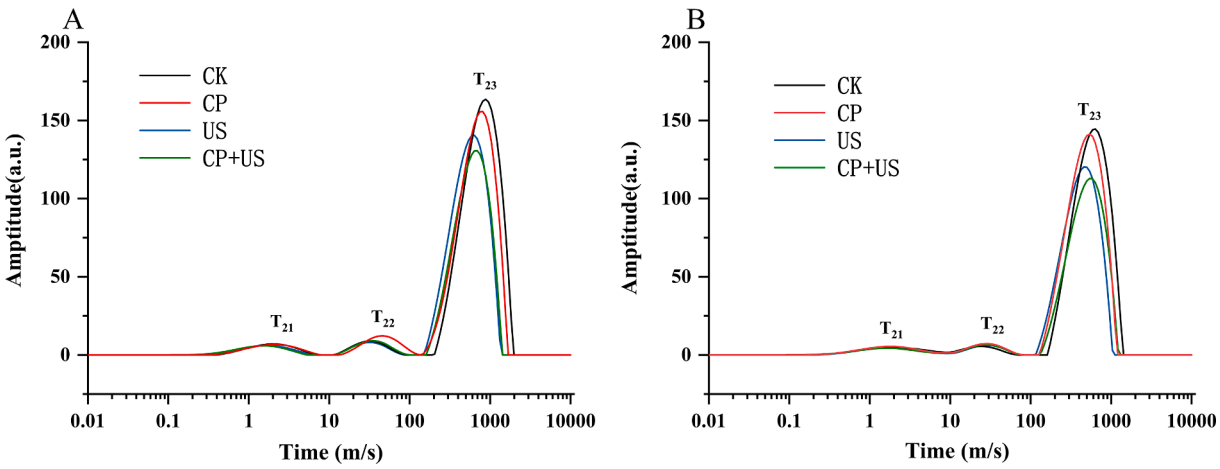

Fig. 2. Low field nuclear magnetic resonance spectrum of fresh-cut potatoes on day 4 of storage (A). Low field nuclear magnetic resonance spectrum of fresh-cut potatoes on day 8 of storage (B). T_{21}, bound water; T_{22}, immobilized water; T_{23}, free water.

days of storage. The results also showed that the bacteriostatic effect of the CP + US treatment was significantly better than that of the single treatment ($P < 0.05$), and it also within the acceptable microbial limit during the storage period of 8 d. It has been reported that the US treatment alone produces a large number of cavitation bubbles that increase the temperature and pressure of the cavitation zone, resulting in microbial inactivation [6]. The combined treatment further enhanced the bacteriostatic effect, possibly since short-term cavitation of ultrasound destroyed the cell wall of microorganisms, thereby improving the contact area between CP and the bacteria [30]. These results are consistent with those of a previous study that combined treatment with US and ε-polylysine inhibited microbial growth in fresh-cut lettuce [31].

3.2. Effect of US combined with CP treatment on total color difference

We estimated the changes in surface color and total colors differences in fresh-cut potatoes treated with US and CP (Fig. 1C, D). The ΔE value is an important indicator of the shelf-life and marketability of fresh-cut products. The ΔE values for CP, US, and CP + US groups were significantly lower than that of the CK group ($P < 0.05$). During the 8-day storage period, the ΔE of the US group was significantly lower than that of the CP group ($P < 0.05$), but not significantly different on day 8 ($P > 0.05$). Treatment with US alone reduces color change by inhibiting the activity of browning-related enzymes [32], while the CP coating reduces browning by inhibiting microbial growth and water loss [18]. Notably, at the initial stage of storage, we observed no significant difference in ΔE between US and CP + US ($P > 0.05$), but the difference was significant from day 6 ($P < 0.05$); the combined treatment showed the best browning inhibition effect. This may be because in the early stages of storage, there was little US-induced damage to cells; therefore, the CP could not enter the cells and hence could not regulate enzyme activities and bacterial growth.

3.3. Effect of US combined with CP treatment on texture and quality properties

Texture properties and quality characteristics such as pH, soluble solids and cooking loss rate affect the acceptability of fresh-cut potatoes. Changes in firmness, brittleness, chewiness, soluble solids, pH and cooking loss rate of fresh-cut potatoes during storage are listed in Table 1. The texture parameters showed no significant difference between the different treatment groups in the first 2 days of storage ($P > 0.05$). From day 4, the US and CP + US treatment groups were significantly delayed the decrease of firmness and chewiness ($P < 0.05$). US could increase the homogenization of water-soluble substances in fresh-cut potatoes, thereby increasing their firmness without damaging cells [12]. In the later period of storage, a decrease in flexibility was observed in the control group due to microbial infection and water condition. CP and US treatments could reduce the loss of moisture and the number of microorganisms, thereby delaying the reduction in chewiness of fresh-cut potatoes.

Table 2
Transverse relaxation time (T_{23}) and free water proportion (A_{23}) of fresh-cut potatoes on days 4 and 8.

	Day 4		Day 8	
	T_{23}(m/s)	A_{23}(%)	T_{23}(m/s)	A_{23}(%)
CK	888.48 ± 2.55^{a}	91.26 ± 0.89^{a}	636.82 ± 3.62^{a}	90.89 ± 0.26^{a}
CP	811.98 ± 4.78^{a}	90.10 ± 0.76^{a}	541.59 ± 4.56^{a}	89.32 ± 1.23^{a}
US	636.83 ± 5.34^{b}	89.53 ± 0.56^{ab}	460.58 ± 3.82^{b}	87.13 ± 0.67^{a}
CP + US	690.55 ± 3.22^{b}	88.33 ± 0.82^{b}	541.59 ± 3.66^{b}	86.53 ± 0.89^{b}

Values are means ± standard deviation (n = 3). Different letters represent significant differences between different treatment groups at the same storage time ($P < 0.05$).

The soluble solid content of fresh-cut potatoes showed a downward trend due to the enhanced respiration in the later stage of storage, while nutrients such as sugars were consumed in large quantities. Following treatment with CP and US, the decrease in soluble solids in potato slices was mitigated along with the loss of nutrients in fresh-cut potatoes, possibly due to the inhibition of microorganisms on the surface of fresh-cut potatoes [18,31]. Table 1 shows the gradual decrease in pH of fresh-cut potatoes during storage. The decrease in pH may be the result of respiration, the increasing concentration of CO_2 during storage and dissolution into the cell's liquid medium resulting in increased acidity [12]. The pH value of the treatment group was significantly different from that of the control group from the day 4 ($P < 0.05$). The pH of the CP + US treatment group was significantly higher than that of the control group at the later stage of storage ($P < 0.05$) since CP + US treatment reduced respiratory intensity and metabolism-related enzyme activities. We also observed no significant difference in cooking loss rate between the treated fresh-cut potatoes and control groups, suggesting that the treatment had no adverse effect on the nutrients of fresh-cut potatoes.

3.4. Effect of US combined with CP treatment on water status and distribution

The internal water fluidity of fruits and vegetables increases during storage, which increases water loss and decline quality [33]. The change in water state of fresh-cut potatoes during storage can be directly

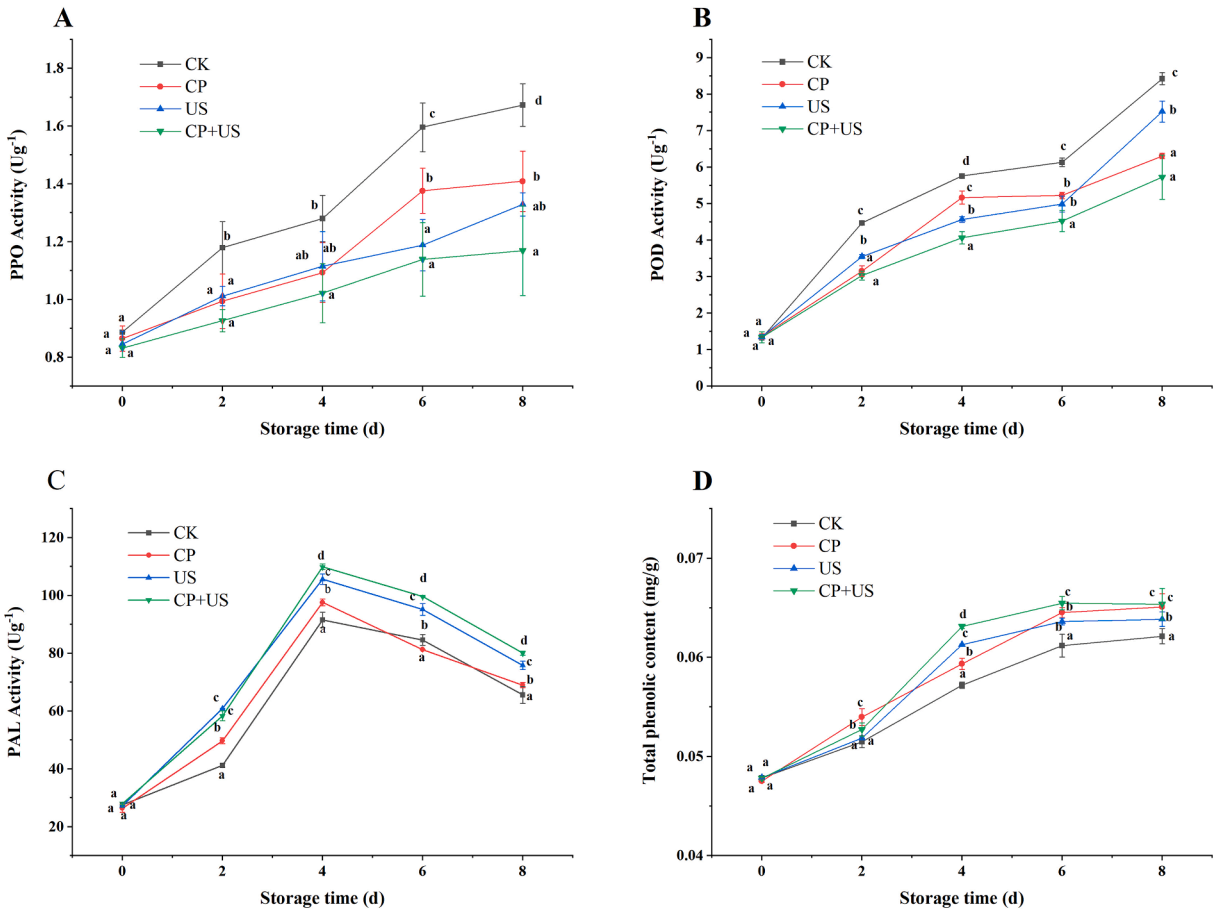

Fig. 3. Changes in PPO (A), POD (B), PAL (C), and total phenolic content (D) of fresh-cut potatoes under different treatments (CK, CP, US, and CP + US) during storage at 4 °C for 8 days. Data are expressed as the mean ± standard deviation. The various treatments at the same storage time are expressed by different letters showing significant differences ($P < 0.05$).

observed using LF NMR. Fig. 2 shows the NMR spectrum of different treatments stored on days 4 and 8. According to the different lateral relaxation time, the water in fresh-cut potatoes can be divided into T_{21} (0.01–10 ms), T_{22} (10–100 ms), and T_{23} (100–1,500 ms), which represent the moisture with different degree of combination and fluidity. Table 2 lists the effects of different treatments on relaxation time (T_{23}) and free water ratio (A_{23}) during cold storage of fresh-cut potatoes. T_{23} and A_{23} decreased with the increase in storage duration, which may be attributed to the decrease in free water due to transpiration, respiration, and cell metabolism during storage. On day 4 of storage, A_{23} of treated fresh-cut potatoes was lower than that of the control group, showing a trend of CP + US < US < CP, and the same effect on day 8. Conversely, with the decrease in free water during storage, the concentration of CP increased after entering the cell, which significantly inhibited browning. The cavitation produced by US accelerated the migration of macromolecular substances, while CP entered the cells, resulting in a higher preservation effect [34].

3.5. Effect of US combined with CP treatment on the activities of browning-related enzymes and total phenolic content

The browning system of fresh-cut fruits and vegetables is complex and influenced by various factors, including the amount of substrate, the degree of cell damage, and enzyme activities [35]. The effects of cactus CP, US, and the combined treatment of PPO, POD, and PAL, and the total phenolic content of fresh-cut potatoes from 8 days of storage are shown in Fig. 3.

PPO is an intracellular o-diphenol oxidase in higher plants and fungi [36]. PPO activity was significantly lower in the US and CP treatment groups than in the CK group ($P < 0.05$), except on day 4. US treatment can destroy the structure and activity of PPO [37]. However, it remains unclear how CP inhibits PPO activity. Based on previous reports, we speculate that the protective film formed by CP on the surface of fresh-cut potatoes isolated the tissues from external oxygen, thereby delaying oxidation of polyphenol substrates to quinones, ultimately decreasing PPO activity. The CP + US treatment group maintained the lowest levels of PPO activity during the storage period (Fig. 3A). Ultrasound affects mass transfer between food and soaking medium. As a liquid immersion medium, CP enhances the effect of ultrasound, while the pressure around the cell is rapidly compressed and expanded due to the sponge effect, thereby reducing PPO activity [38]. This is in line with the results of Zhu et al. [39], who observed that ultrasound (in combination with purslane extract) can inhibit enzyme activities.

POD is a key enzyme in phenolic metabolism involved in the enzymatic browning of fresh-cut products [40]. Fig. 3B illustrates the effects of CP and US treatments on POD activity during the 8-day storage period. POD activities were significantly lower in samples treated with CP or US ($P < 0.05$). During days 4–6, POD activity in the CP treatment group was transiently higher than that in the US treatment group. At the end of the storage period, the CP treatment was superior to the US treatment in reducing POD enzyme activity ($P < 0.05$). This indicated that both CP and US treatment could regulate POD activity, and that their effects are influenced by storage duration. In addition, the combined treatment had the strongest inhibitory effect on POD activity, possibly since US-induced damage to the cell membranes of fresh-cut potatoes allowed CPs to enter and enhance antioxidant activity,

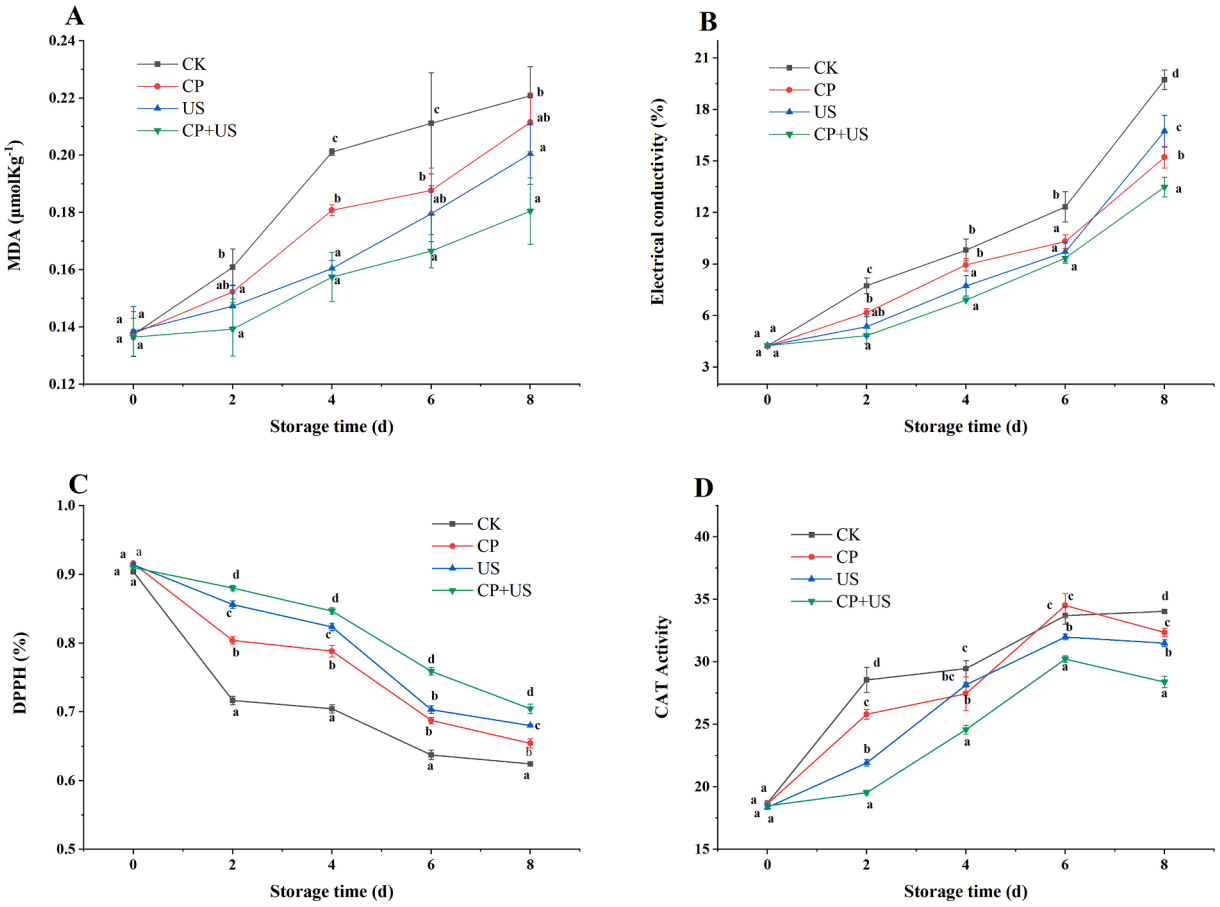

Fig. 4. Changes in MDA (A), electrical conductivity (B), DPPH (C), and CAT (D) of fresh-cut potatoes under different treatments (CK, CP, US, and US + CP) during storage at 4 °C for 8 days. Data are expressed as the mean ± standard deviation. The various treatments at the same storage time are expressed by different letters showing significant differences ($P < 0.05$).

thereby inhibiting POD activity, which is consistent with previous findings [41].

In plants, phenols are produced by the enzyme PAL, which is activated by traumatic stress during minimum processing. The activity of PAL first increased, then decreased during the 8 days of storage (Fig. 3C). During the first 4 days, treatment with CP + US or US alone significantly increased PAL activity ($P < 0.05$) compared with that in the CK and CP groups. This may be because the cavitation generated by ultrasound stimulates a stress response in cells, thereby increasing the activity of PAL [42]. PAL activity peaked on day 4 at 91.5 U/g in the CK group and 110 U/g in the combined treatment group. During the last 4 days of storage, PAL activity continued to decrease due to cell aging, thereby reducing browning. At the end of storage, PAL activity of the combined group was 1.05 times that of the control group. This indicates that the stress response caused by cutting in the control group decreased at later storage. However, the abiotic stress in the fresh-cut potatoes after the combined treatment enhanced the mass transfer efficiency through cavitation, thereby enhancing PAL activity [34].

Polyphenols, important components of fruits and vegetables, exhibit antioxidant activity. In addition to neutralizing lipid free radical chains and preventing hydroperoxides from becoming reactive oxygen radicals, polyphenols also chelate redox active metal ions [43]. The total phenolic content of all treatment groups increased during storage (Fig. 3D), and was significantly higher in the treatment groups than in the CK group ($P < 0.05$). After 4 days, the combined treatment group showed the highest levels of total phenols. Meanwhile, on day 8 of storage, the total phenolic content of the combined treatment group was 1.22 times that of the CK group. A previous study reported that US treatment improves the total phenolic content of fresh-cut sweet potatoes [44]. Therefore, the combination treatment might have contributed to the maintenance of larger levels of total phenolic content in this study. The total phenolic content tended to remain stable at the later stages of storage. This may be caused by the continuous oxygen consumption during browning and the decreased PAL activity.

3.6. *Effect of US combined with CP treatment on membrane integrity*

MDA is used as a marker to reflect the degree of lipid peroxidation in the tissues and cell membranes of fresh-cut products [45]. During the storage period, the MDA content of all groups gradually increased (Fig. 4A). Both US and CP had an inhibitory effect on MDA levels; however, there were no significant differences between them ($P > 0.05$). The antioxidant effects of CP eliminate the free radicals produced by cells, thus preventing lipid peroxidation [46]. MDA levels were lowest in the CP + US group, although there was no significant difference in MDA contents between the CP + US and US groups. Under certain conditions, the CP + US treatment did not destroy the cellular structure of fresh-cut potatoes. However, it inhibited the oxidation of membrane lipids and reduced the production of MDA, thus effectively delaying the enzymatic browning of fresh-cut potatoes during storage.

Relative conductivity, a crucial sign of cell membrane permeability [47], increased with an increase in storage time, indicating a gradual loss of cell membrane integrity during storage (Fig. 4B). There was no significant difference in relative conductivity between the US and CP + US groups at 6 days before storage, suggesting that the addition of CP treatment had little effect on US-induced cell permeability. On day 8 of storage, electrical conductivity was lowest in the CP + US treatment group, indicating that the combined treatment could maintain the

Table 3
The detected VOCs of fresh-cut potatoes by GC-IMS.

Count	Compound	CAS	Formula	MW	RI	Rt [*sec*]	Dt [a.u.]
Alcohols (7)							
	(E)-3-Hexen-1-ol	C928972	$C_6H_{12}O$	100.2	841.8	293.335	1.51181
	2-Hexanol	C626937	$C_6H_{14}O$	102.2	788.3	242.344	1.25966
	5-methyl-2-Furanmethanol	C3857258	$C_6H_8O_2$	112.1	955.1	429.793	1.25119
	3-Methyl-1-butanol	C123513	$C_5H_{12}O$	88.1	739.7	207.872	1.48383
	(Z)-3-nonen-1-ol	C10340235	$C_9H_{18}O$	142.2	1150.4	851.885	1.41089
	linalool	C78706	C10H18O	154.3	1129	801.41	1.76807
	n-Hexanol	C111273	C6H14O	102.2	872.2	322.291	1.99147
Aldehyde (13)							
	(E)-2-octenal	C2548870	$C_8H_{14}O$	126.2	1067.8	656.72	1.33205
	(E)-hept-2-enal	C18829555	$C_7H_{12}O$	112.2	951.7	425.031	1.66136
	Heptanal	C111717	$C_7H_{14}O$	114.2	896.9	348.004	1.3378
	(E)-2-hexenal	C6728263	$C_6H_{10}O$	98.1	847.2	298.431	1.17791
	(E)-2-pentenal	C1576870	C_5H_8O	84.1	752.4	216.609	1.1052
	Pentanal	C110623	$C_5H_{10}O$	86.1	704.3	183.52	1.19424
	3-methylbutanal	C590863	$C_5H_{10}O$	86.1	645.6	153.74	1.17788
	Octanal	C124130	$C_8H_{16}O$	128.2	982.4	468.247	1.42274
	Furfural	C98011	$C_5H_4O_2$	96.1	803.4	256.756	1.0712
	butanal	C123728	C_4H_8O	72.1	596.6	132.134	1.28345
	Propanal	C123386	C_3H_6O	58.1	501.1	89.958	1.05483
	E,E-2,4-nonadienal	C5910872	$C_9H_{14}O$	138.2	1187.3	939.358	1.3454
	3-methylthiopropanal	C3268493	C_4H_8OS	104.2	914	372.061	1.08758
Ketones (7)							
	1-octen-3-one	C4312996	$C_8H_{14}O$	126.2	975	457.811	1.27023
	cyclohexanone	C108941	$C_6H_{10}O$	98.1	894.3	344.298	1.14499
	3-Pentanone	C96220	$C_5H_{10}O$	86.1	670.6	164.769	1.35415
	acetone	C67641	C_3H_6O	58.1	509	93.445	1.13427
	2-Butanone	C78933	C_4H_8O	72.1	605.1	135.874	1.04354
	6-methylhept-5-en-2-one	C110930	$C_8H_{14}O$	126.2	935.8	402.659	1.17148
	heptan-2-one	C110430	$C_7H_{14}O$	114.2	914.8	373.222	1.254
Esters (7)							
	1-methoxy-2-propyl acetate	C108656	$C_6H_{12}O_3$	132.2	842.8	294.261	1.15126
	Ethyl butyrate	C105544	$C_6H_{12}O_2$	116.2	790.8	244.688	1.56041
	methyl 3-methylbutanoate	C556241	$C_6H_{12}O_2$	116.2	771.1	229.399	1.51338
	acetic acid ethyl ester	C141786	$C_4H_8O_2$	88.1	609.8	137.931	1.09793
	acetic acid	C64197	$C_2H_4O_2$	60.1	589.8	129.107	1.13064
	4-hydroxynonanoic acid, lactone	C104610	$C_9H_{16}O_2$	156.2	1342.7	1306.802	1.41569
	Ethyl cinnamate	C103366	$C_{11}H_{12}O_2$	176.2	1463.3	1591.873	1.99429
Hydrocarbons (6)							
	Decamethylcyclopentasiloxane	C541026	$C_{10}H_{30}O_5Si_5$	370.8	1162.3	880.098	1.81467
	Ocimene	C13877913	$C_{10}H_{16}$	136.2	1029.8	566.931	1.26255
	Phellandrene	C99832	$C_{10}H_{16}$	136.2	1001.2	499.289	1.22466
	Hexamethylcyclotrisiloxane	C541059	$C_6H_{18}O_3Si_3$	222.5	806.3	259.513	1.47105
	Hexamethyldisiloxane	C107460	$C_6H_{18}OSi_2$	162.4	683	170.284	1.31054
	Octamethylcyclotetrasiloxane	C556672	$C_8H_{24}O_4Si_4$	296.6	985.7	472.936	1.67566
Furans (2)							
	2-pentyl furan	C3777693	$C_9H_{14}O$	138.2	990.1	479.118	1.24488
	2,5-Dimethylfuran	C625865	C_6H_8O	96.1	701.6	181.682	1.35597
Others (4)							
	2-ethyl-5-methylpyrazine	C13360640	$C_7H_{10}N_2$	122.2	1003.1	503.651	1.66897
	Propylsulfide	C111477	$C_6H_{14}S$	118.2	883.6	333.179	1.17477
	Propanoic acid	C79094	$C_3H_6O_2$	74.1	707	185.358	1.08157
	2-Propanol	C67630	C_3H_8O	60.1	542.8	108.356	1.21032

integrity of cell membranes. Notably, relative conductivity was lower in the US treatment group than in the CP treatment group on day 6 of storage, then rapidly increased in the US group and finally exceeded that of the CP group on day 8. This may be because US-induced damage to the cell membrane becomes increasingly obvious with increasing storage time, and the combined action with CPs delayed the US-induced damage. Overall, the CP + US treatment significantly delayed the increase in MDA levels and oxidative damage to membranes caused by cutting, which is consistent with the results of Xu et al. [34].

3.7. Effect of US combined with CP treatment on antioxidant capacity

Plant antioxidant ability can be assessed using the DPPH free radical scavenging capacity [48]. Individual treatment with CP or US alone improved the antioxidant capacity of fresh-cut potatoes (Fig. 4C), with the US group exhibiting better results. US treatment has been reported to produce abiotic stress on fresh-cut potatoes, thus inducing a higher level of antioxidant capacity [44]. In this study, we found that CP + US treatment improved the antioxidant capacity of potatoes, while the CP + US group showed the least amount of decrease in antioxidant capacity throughout the storage period. As known to all, there is a positive correlation between antioxidant capacity and total phenol content [49]. As discussed in Fig. 3, CP + US significantly increased the total phenol content compared with other treatment groups. Thus, CP + US treatment showed the best free radical scavenging ability in fresh-cut potato. This improved the antioxidant capacity of fresh-cut potatoes and reduced the tissue damage caused by reactive oxygen species.

CAT is one of the most important enzymes for scavenging free radicals [50]. The CAT activity of all groups showed an upward trend (Fig. 4D), although the increase was more gradual in the experimental treatment groups. In the treatment groups, CAT activity peaked on day 6, then decreased noticeably; however, in the CK group, the rate of increase in CAT activity decreased only slightly after day 6. Based on this, we speculated that CAT activity in the CK group peaked on day 8.

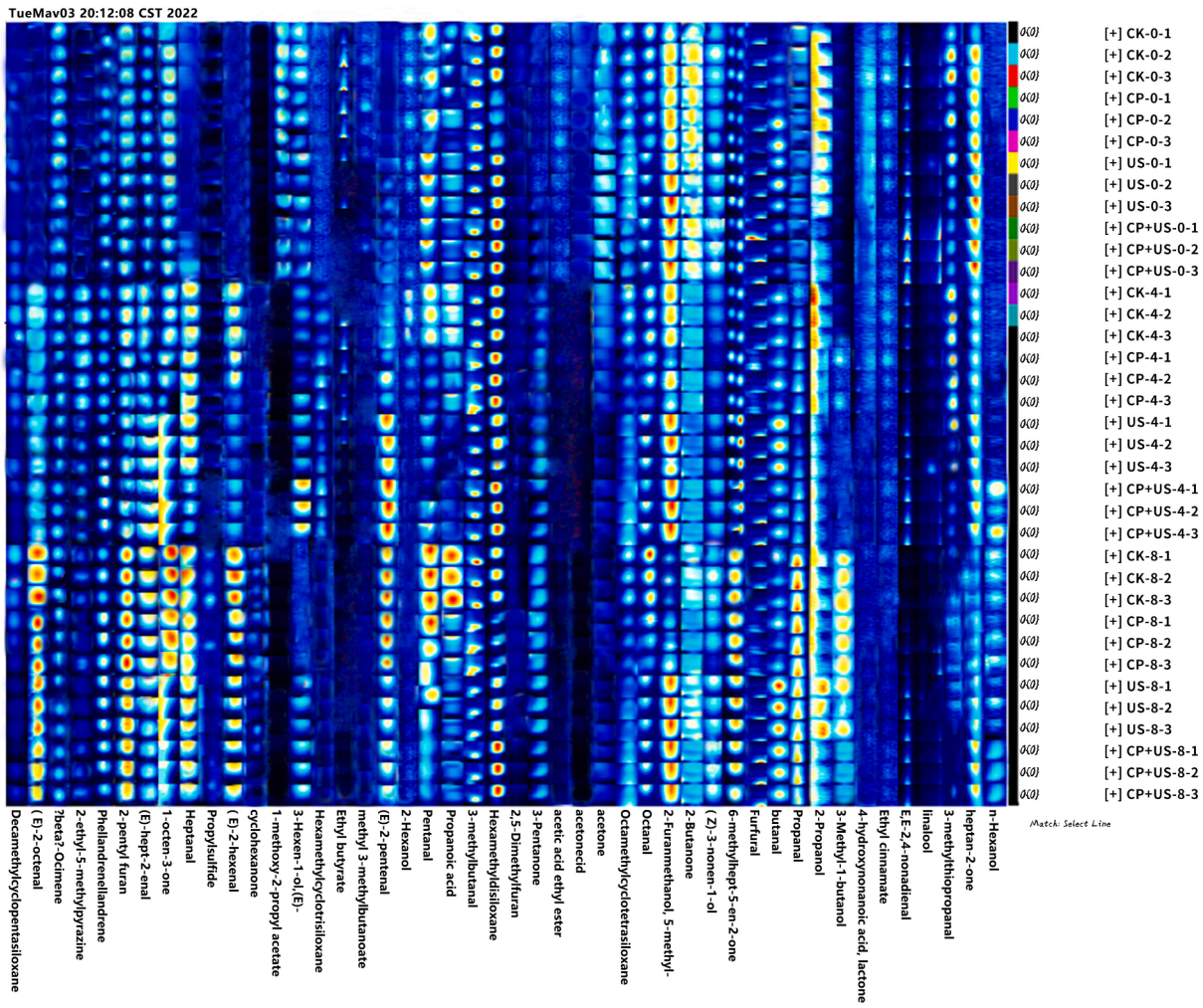

Fig. 5. Fingerprint comparison of volatile organic compounds (VOCs) in fresh-cut potatoes determined using HS-GC-IMS. Each row represents all signal peaks selected in a sample, while each column represents the signal peak of the same volatile compounds in different treatments. HS-GC-IMS was conducted in triplicate.

Therefore, US or CP treatment may accelerate peak CAT activity in fresh-cut potatoes. From day 6, the CAT activity was significantly higher in the CP group comparing with the US group ($P < 0.05$), possibly since CP treatment produces more H_2O_2, which increases CAT activity [51]. CAT activity was lowest in the combined treatment group throughout the storage period, indicating that combined treatment reduces intracellular accumulation of reactive oxygen species and free radicals, thus reducing damage to the cell membrane [44].

3.8. *Effect of combined treatment on volatile organic compounds in fresh-cut potatoes*

Volatile organic compounds are closely associated with the flavor quality of fresh-cut products, which greatly affects sensory evaluation among consumers [52]. Although our results indicated that different treatments had significant effects on the browning of fresh-cut potatoes, the changes in volatile components following different durations of storage remain unclear. Therefore, we used fresh-cut potatoes stored for 0, 4, and 8 days to explore the effects of different treatments on the flavor compounds of fresh-cut potatoes during storage. The volatile compounds of fresh-cut potatoes treated with different treatments were qualitatively analyzed based on the NIST and IMS databases. We identified 46 volatile compounds discovered, including alcohols, aldehydes, ketones, esters, hydrocarbons, and furans (Table 3). To directly compare the volatile flavor compounds between groups, we used the Gallery plugin in the GC-IMS LAV software to generate chemical fingerprints and examine the variations among volatile flavor compounds.

Fig. 5 shows the overall comparison and analysis across all samples. Hydrocarbons such as decamethylcyclopentasiloxane, ocimene, phellandrene, hexamethylcyclotrisiloxane, and hexamethyldisiloxane remained basically unchanged during storage, with no significant differences between treatments.

Hydrocarbon compounds can impart a refreshing odor to some extent, but due to their high threshold, it is not easy to cause an olfactory response, so non-hydrocarbon compounds are selected as the main source of flavor substances. Esters, including 1-methoxy-2-propyl acetate, ethyl butyrate, methyl 3-methylbutanoate, and acetic acid, were detected only in samples collected on day 0. Although hydrocarbons and esters do not play a decisive role in overall flavor, they may enhance or reduce the overall aroma of potatoes [53]. Our results showed that different treatments had different inhibitory effects on the contents of (E)-2-octenal, (E)-heptyl-2-enal, heptanal, (E)-2-hexenal, pentaldehyde, furfural, and propionaldehyde. The combined treatment had the most significant inhibitory effect and may therefore suppress odor production in fresh-cut potatoes during storage. Eight aldehydes, namely pentanal, hexanal, nonanal, (E)-2-octenal, (E)-4-heptadienal, (E)-2-nonenal, (E)-2-nonenal, and 2-decenal, have been reported as potential contributors to potato odor [54]. The levels of 1-octen-3-one gradually increased during storage and showed significant inter-group differences. Xu et al. reported that the main volatile compound in raw and fresh-cut potatoes is 1-octen-3-one; thus, the CP + US treatment may help to preserve flavor by suppressing the increase of 1-octen-3-one [42]. Based on this,

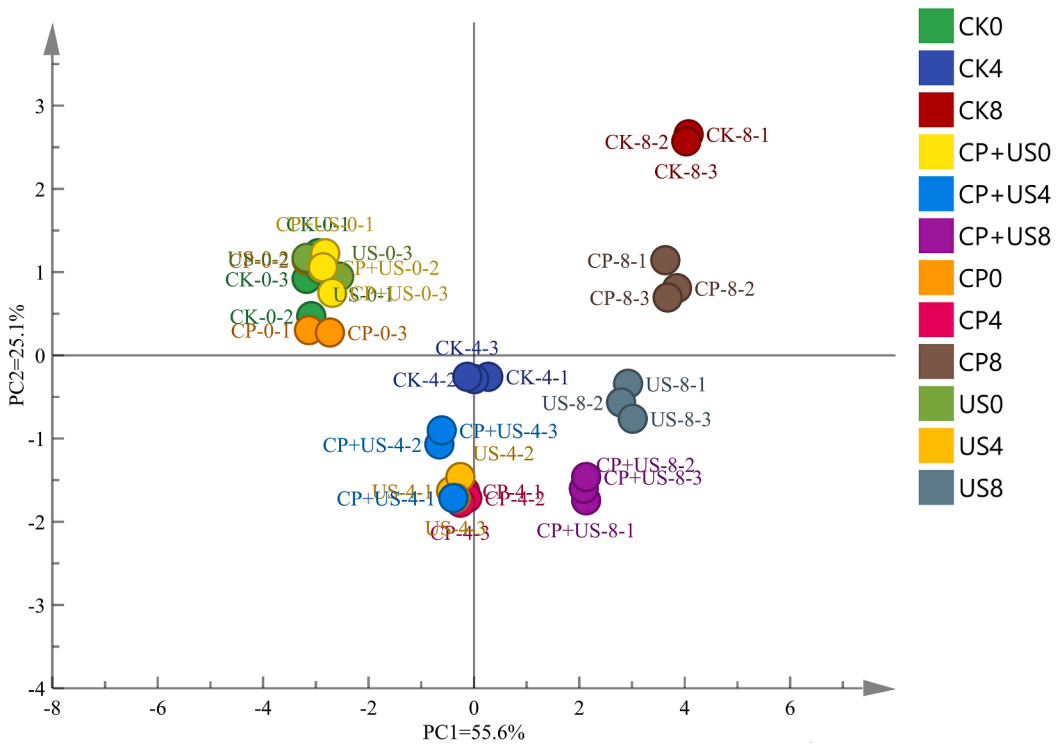

Fig. 6. PCA analysis of volatile components in the various treatments of fresh-cut potatoes during storage. CK0, CK4, CK8, CP0, CP4, CP8, US0, US6, US8, CP + US0, CP + US4, and CP + US8 represent different treatments stored for 0, 4, and 8 days.

we speculated that the compound treatment reduced the production of a peculiar smell during storage by inhibiting the increase in aldehydes level, which has practical significance for maintaining the flavor of fresh-cut potatoes.

Through dimensionality reduction, multivariate statistical analysis technique principal component analysis (PCA) reduces variables to a small number of representatives [55]. In our analysis, PC 1 and PC 2 explained a total of 80.7 % of the variation in the data. Data points for different storage times were easily distinguishable (Fig. 6), suggesting that the volatile compounds of potatoes significantly change with storage duration. On day 0, the distances between different treatments were relatively low, indicating that the effects of different treatments were not obvious during the initial stages of storage. As storage duration increases, so does the distance between different treatment groups, indicating differences in the volatile compound composition of different treatment groups during latter stages of storage. This is consistent with the fingerprint analysis; therefore, PCA can be used to distinguish fresh-cut potatoes at different storage periods, which can help to determine their freshness.

4. Conclusions

In this study, we used CP to enhance the preservative effects of US. The combined treatment of CP and US suppressed the number of microorganisms within an acceptable range (<5.0 logCFU/g), which reduced the mobility of water while maintaining the appearance quality and texture properties. CP + US treatment significantly inhibited the decrease of PPO and POD activities, while maintaining higher PAL activity and total phenolic content, and had the lowest MDA and conductivity, which not only reduced the degree of membrane lipid peroxidation, but also maintained cell membrane integrity. CP + US treatment also improved the antioxidant capacity of fresh-cut potatoes, thus reducing the damage to cell membranes caused by the accumulation of free radicals. These factors contributed to the inhibition of browning and helped to retain the quality of fresh-cut potatoes. In addition, the combined treatment held the flavor considerably by inhibiting the increase of aldehydes and reducing the production of bad flavor compounds during storage. Taken together, our results suggest that combined CP + US treatment can effectively prolong the shelf-life of fresh-cut potatoes, which is significant for the development of novel preservation techniques with potential application in the agricultural industry.

CRediT authorship contribution statement

Dewei Cheng: Conceptualization, Methodology, Data curation, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Qianyun Ma:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Jianhui Zhang:** Data curation, Methodology, Supervision. **Kaili Jiang:** Investigation, Supervision. **Shijia Cai:** Investigation, Supervision. **Wenxiu Wang:** Investigation, Resources, Supervision. **Jie Wang:** Investigation, Resources, Supervision. **Jianfeng Sun:** Conceptualization, Methodology, Data curation, Investigation, Supervision.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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