Quality of bamboo shoots during storage as affected by high hydrostatic pressure processing

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\textbf{ABSTRACT}

The effect of high hydrostatic pressure (HHP) processing on the quality of bamboo shoots during a storage period of 15 d at room temperature was investigated. The results indicated that when compared to other methods, the bamboo shoots treated at 300 MPa for 10 min displayed the best quality when stored. The weight loss and titratable acidity (TA) in these samples presented a minimal increase at the end of storage, from 0\% and 0.1317 g kg\textsuperscript{-1} to 0.67\% and 0.2793 g kg\textsuperscript{-1}, respectively. The respiratory intensity, sensory acceptability, and color of the bamboo shoots were significantly preserved and were 25.39 mg CO\textsubscript{2} kg\textsuperscript{-1} h\textsuperscript{-1}, 7.55, and 77.65, respectively. Moreover, the polyphenol oxidase (PPO) and peroxidase (POD) activity of the treated bamboo shoots were inhibited effectively. In addition, the samples that were treated at 400 MPa for 15 min displayed the lowest firmness and microbiological content which at 51.15 N and 84.6 CFU g\textsuperscript{-1}, respectively, while the samples treated at 300 MPa for 10 min showed slightly higher values. In conclusion, these results demonstrate that HHP treatment can be considered efficient in preserving the quality of bamboo shoots during storage at room temperature.

\textbf{Introduction}

Over 1250 species of edible bamboo have been reported worldwide.\textsuperscript{[1,2]} Bamboo, widely cultivated in Asia, is a rapidly growing plant, which shoots are edible and used as one of the important ingredients in Asian cuisine.\textsuperscript{[3]} Bamboo shoots, which are the tender stalks emerge from the nodes of the (pseudo-) rhizome of bamboo plants, are wrapped in protective, non-edible leaf sheaths, with the edible part consisting of meristematic cell tissue with regions of rapid cell division and differentiation.\textsuperscript{[2,4]} The consumption of bamboo shoots has the benefits of improving digestion, relieving sweating and hypertension, preventing cardiovascular diseases and cancer, because bamboo shoots are rich in functional nutrients such as high-quality protein, vitamins, dietary fiber and bioactive compounds, and low in fat and sugar contents.\textsuperscript{[5–7]} In recent years, fresh bamboo shoot has become increasingly popular all over the world due to its higher nutritional value, however, its tissue lignification and flesh browning lead to rapid deterioration of its edible quality during postharvest.

The rapid increase in the firmness and stiffness from the cut-end toward the tip limits the life span of post-harvest bamboo shoots, which may be the result of various detrimental changes and tissue lignification during aging.\textsuperscript{[4,8]} Luo et al.\textsuperscript{[9]} have reported that postharvest wounding of bamboo shoots will cause an abnormal rise in lignification, Xi et al.\textsuperscript{[10]} had been reported similarly results. Actually,
lignification, occurring during the course of normal tissue development, is a biochemistry process of sealing a plant cell wall by lignin deposition.\textsuperscript{[11]} The lignification of plant tissues involves the polymerization of monolignols mainly derived from the phenylpropanoid pathway, which begins with the Phenylalanine ammonia-lyase (PAL) reaction that forms cinnamate derivatives and ends with the peroxidase (POD) reaction to form the lignin polymer units.\textsuperscript{[12,13]} Therefore, delaying the lignification of bamboo shoots should be an effective way to reduce quality loss during transportation and storage. Until now, various treatments such as chitosan coating,\textsuperscript{[14]} modified atmosphere packaging,\textsuperscript{[15]} gamma irradiation,\textsuperscript{[7]} or 1-methylcyclopropene (1-MCP) treatment\textsuperscript{[16]} have been shown to delay the lignification process, however, the application of ultra-high pressure in the preservation of bamboo shoots has few reports.

High hydrostatic pressure (HHP), also known as Ultra-high pressure (UHP) or high pressure processing (HPP), is a rapidly emerging non-thermal processing technology, which killing pathogenic microorganisms in foods at pressures of 100-1000 MPa and at room temperature or lower, thereby prolonging the shelf life of food and reducing the damage of heat-sensitive food ingredients.\textsuperscript{[17–20]} Unlike in thermal treatment, HHP can keep the food temperature at the set temperature all the time, because the pressure transmittance is instantaneous and uniform throughout the food, regardless of its size or shape.\textsuperscript{[21,22]} The effect of HPP on food quality characteristics is mainly attributed to the stability of covalent bonds to high pressure,\textsuperscript{[23]} which not only ensure food quality, including not only texture, shape, and color, but also the flavor and nutritional characteristics of fresh food.\textsuperscript{[24–26]} Packaged food is processed under HHP to achieve sterilization, change of enzyme activity, material modification, and accelerating of decelerating physical and chemical reactions.\textsuperscript{[27,28]} Zhang et al. reported that HHP technology mutates basic physical properties by breaking weak bonds such as hydrogen bonds.\textsuperscript{[29]} In the past two decades, HHP has been widely applied to food industries such as meat product, dairy product, starch-based product, seafood, puree, juice and other food industries.\textsuperscript{[30]} However, few publications about the bamboo shoot by ultra-high pressure treatment are available.

The aim of our study was to investigate the effects of HHP treatment on the quality of fresh bamboo shoots during storage. The sensory, total number of colonies and enzyme activities of bamboo shoot, before and after different HHP treatment, were comparatively analyzed. Changes in quality under HHP treatments were observed to provide a theoretical basis for bamboo shoots storage and subsequent deep processing.

**Materials and methods**

**Materials**

Bamboo shoots were provided by Pengzhou Qiangsheng Agricultural Development Co. Ltd. (Sichuan, China). Plastic vacuum packaging materials (15 cm × 25 cm, δ 0.06 mm) were supplied by Xizhilong Packing Material Co. Ltd. (Hebei, China). The HHP equipment was manufactured by Shanghai Wodi Intelligent Equipment Co. Ltd. (Shanghai, China). Plate count agar was purchased from Beijing Oboxing BiotechnologyCo. Ltd. (Beijing, China). Polyvinyl pyrrolidone, guaiacol, pyrocatechol, hydrogen peroxide (H₂O₂) and other reagents were all supplied by Chengdu Kelong Chemical Reagent Factory (Sichuan, China)

**Processing technology for HHP of bamboo shoot**

Fresh bamboo shoots of uniform size and harmless are selected, blanched in boiling water for 2 minutes to kill most of the microorganisms attached to the surface of the bamboo shoots for further processing. The bamboo shoots were blanched for a short time without peeling the outer leaves, which had no effect on the enzymatic activity. After cooled and drained at room temperature, the sample peeled off the outer leaves, washed with pure tap water until no impurities and soil, and cut in half lengthwise. About 20 g of bamboo shoots were vacuum-sealed in plastic vacuum packaging materials.
Table 1. Different treatments of HHP of bamboo shoots.

| Processing number | Processing method | Pressure | Time |
|-------------------|-------------------|----------|------|
| 1 (control)       | Ambient pressure  | -        | -    |
| 2                 | 200 MPa           | 5 min    |      |
| 3                 | 200 MPa           | 10 min   |      |
| 4                 | 200 MPa           | 15 min   |      |
| 5                 | 300 MPa           | 5 min    |      |
| 6                 | 300 MPa           | 10 min   |      |
| 7                 | 300 MPa           | 15 min   |      |
| 8                 | 400 MPa           | 5 min    |      |
| 9                 | 400 MPa           | 10 min   |      |
| 10                | 400 MPa           | 15 min   |      |

All the experiments were performed at 25°C. A total of 10 treatments were designed, as detailed in Table 1, with 30 bags per treatment for a total of 300 bags. The relative indexes were measured every 3 days during the room temperature storage period of 15 days.

**Weight loss and respiratory intensity**

The weight loss of bamboo shoots was evaluated using the method reported by Li et al. The weighing method was used to determine the weight loss rate, which was expressed as follows:

\[
\%WL(t) = \frac{M_0 - M_t}{M_0} \times 100\%
\]

where \(\%WL(t)\) is the percentage weight loss at time \(t\), \(M_0\) is the initial weight of the sample and \(M_t\) is the sample weight at time \(t\). The rate of CO₂ concentration was measured by a respiratory intensity meter and expressed as mg CO₂ kg⁻¹ h⁻¹. The respiratory intensity of bamboo shoots was evaluated with JZ-3150 H Respiratory Intensity Meter (Beijing Kyushu Space Science and Trade Co. Ltd., China) according to the method reported by Zhao et al.

**Firmness and titratable acidity (TA)**

AS showed in Figure 1, specimens (20 mm × 10 mm) were excised from the middle part of the bamboo shoots to determine the firmness. A TA.XT Plus Texture Analyzer (Stable Microsystems Ltd., UK) with a standard cylindrical probe (P36R) was used for the firmness, with the following parameters: load cell = 1 kg, pretest speed = 2.0 mm/s, test-speed = 1.0 mm/s, posttest speed = 2.0 mm/s, compression degree = 70%, time = 5.0 s, and trigger force = 0.05 N. Each sample was measured 10 times, and the results regarding the peak force of compression (N) were reported. TA content was determined using the method reported by Xu et al. and Xing et al. 5 grams sample of bamboo shoots was homogenized with 100 mL of boiled distilled water (pH 8.3). The mixture solution was titrated with 0.10 M NaOH to pH 8.3. The TA content in the slice sample was expressed as mg acid per 100 g.

**Polyphenol oxidase (PPO) and peroxidase (POD) activity**

The PPO activity in the bamboo shoot was performed according to the method conducted by Li et al., Xing et al. and Xing et al. with some modification. Sample tissue (10 g) was homogenized in an ice bath with 20 mL extraction buffer (sodium phosphate buffer with 2.5 g/100 g polyvinylpolypyrrolidone, 0.1 mol/L, pH 7.0, 4°C) for 4 min. The obtained solution was centrifuged at 4°C with 11,000 g for 15 min. The reaction solution comprised 2 mL substrate solution (0.05 mol/L catechol in 0.1 mol/L phosphate buffer, pH 7.0) and 0.1 mL crude extract. The catechol oxidation rate
was evaluated at 412 nm for 2 min at room temperature, and the activity unit was defined as an increase of 0.01 in absorbance for one minute.

POD activities in bamboo shoots was investigated as the method reported by Xing et al.\cite{38} and Li et al.\cite{39} 10 g bamboo shoot tissue was homogenized in 20 mL phosphate buffer (25 mmol L\(^{-1}\), pH 7.0, containing 1 mmol L\(^{-1}\) ethylene diamine tetraacetic acid and 0.5 g L\(^{-1}\) polyvinyl pyrrolidone) and then centrifuged at 4°C with 11,000 g for 15 min. 0.2 mL enzyme extract was incubated at 30°C in 2 mL buffered substrate (pH 7.0, 100 mmol L\(^{-1}\) sodium phosphate and 5 mmol L\(^{-1}\) guaiacol) for 5 min and the absorbance measured at 470 nm every 30 s for 120 s after adding 0.8 mL of H\(_2\)O\(_2\) (15 mmol L\(^{-1}\)). POD activity in bamboo shoots was expressed as U g\(^{-1}\) (U = 0.01 D-absorbance\(_{470 \text{ nm}}\) min\(^{-1}\)).

**Sensory acceptability and color**

Sensory acceptability of bamboo shoots was evaluated by a 30-member trained panel (15 males and 15 females) ranging from 20 to over 35 years old by suitably modifying the methods of Wichchukit et al.\cite{40} and Gabriela et al.\cite{41} The 9-point hedonic scale was used to tested the surface character and consumer acceptance of bamboo shoots to assess the degree of preference/aversion of consumers (1-dislike extremely to 9-like extremely). The L* value was measured using a precision chroma meter (D65 Standard Light Sources, Shenzhen Weifu Photoelectric Technology Co. Ltd., China) according to the work of Xia et al.\cite{42} and Xu et al.\cite{28} 10 g bamboo shoot was covered with a brown plate and the measurement carried out avoiding light. Before measuring, the chroma meter was calibrated to a black and white standard.

**Detection of microbiological content**

Microbiological analysis was performed according to the methods suggested by Wang et al.\cite{33} and Xing et al.\cite{33} 10 g sample bamboo shoot and 90 mL sterile NaCl solution were homogenized with
a Stomacher for 60 s. The 1 mL volume of the diluted sample solution was pour-plated on plate count agar (PCA) and incubated at 30°C for 24 h to obtain the total bacterial count.

**Statistical analysis**

The data analysis in this research was conducted using SPSS25.0 software (SPSS, Inc., Chicago, IL). The mean values were calculated and reported as the mean ± S.D. (n = 3). One-way analysis of variance followed by the least significant difference (P ≤ 0.05) was performed on the data to determine the significant factors.

**Results and discussion**

**Weight loss and respiratory intensity**

Weight loss of fresh produce is an important parameter because it affects the quality and shelf life. As shown in Figure 2, during the storage period of 15 days, the weight loss rate of non-treated and HHP-treated bamboo shoots showed an obvious upward trend. A significant difference (P < 0.05) in weight loss was observed among the control and HHP treated samples. In the control group, the weight loss was 1.46% after 15 days at 25°C and was significantly different from other groups (P < 0.05). Bamboo shoots in the HHP treatment at 300MPa for 5min and 10 min had the lower weight loss with no significant difference between the two (P > 0.05), which were 0.68% and 0.67%, respectively. On the other hand, water loss not only caused the bamboo shoot to wilt, but also adversely affect the respiration of fresh bamboo shoot after harvest. Figure 3 shows that the respiratory intensity of all treatments decreased during storage, and the downward trend was greatly in the initial storage period, but tended to be gentle at the later period of storage. The reason for the decrease in the respiratory intensity during the postharvest period might be that the HHP treatment resulted in a low gas concentration (e.g. CO₂ and O₂) in bamboo shoot tissues. The respiratory intensity of the controls was higher than that of HHP-treated bamboo shoots. At the end of storage, the respiratory intensity of the controls decreased from 163.57 mg CO₂ kg⁻¹ h⁻¹ to 56.41 mg CO₂ kg⁻¹ h⁻¹, while the bamboo

![Figure 2](image-url). Effect of HHP treatment on the weight loss of bamboo shoots.
Figure 3. Effect of HHP treatment on the respiratory intensity of bamboo shoots.

A shoot treated by 300MPa for 10 min had a significantly (P < .05) respiratory intensity loss (25.39 mg CO₂ kg⁻¹ h⁻¹) than those of other bamboo shoots.

These results showed that HHP treatments could inhibit weight loss and effectively reduce the respiration intensity of bamboo shoots during room temperature storage. Usually, the freshly-harvested bamboo shoots have a moisture content over 90 g/100 g, which continuously evaporate water during the metabolic process of maintaining life activities after harvest. Transpiration is the main way for bamboo shoots to lose water after postharvest. Kleinhenz et al. reported that the weight loss of bamboo (Bambusa oldhamii) shoots reached 22.6% after storage for 6 days at the room temperature, while HHP treatment could significantly reduce the increase in weight loss, which might attributed to the hydration of biomacro molecules including protein, as observed in HHP-treated Granny Smith apple and algarrobo seed. In our research, compared with the above study, the overall lower weight loss of bamboo shoots might be due to the subsequent vacuum packaging suppressing their moisture loss. Moreover, bamboo shoots are living organisms, and undergo respiration process which converts stored sugar to energy in the presence of an oxygen substrate, thus leading to quality loss. As a consequence, in order to control quality loss results from respiration, it is critical to reduce the respiration rate as low as possible on the premise of maintaining the essential living activities. HHP treatment could result in low gas concentrations (e.g. CO₂ and O₂) in bamboo shoots tissue, thereby affecting its respiration patterns. The findings are consistent with the observations of Yi et al. who reported that dramatic reduction or absence in respiration of asparagus samples was noticed in treatments at pressure higher than 200 MPa. The reason for the decreased respiration may be that during the pressurization process, the gases dissolved in the cells and the intercellular space were compressed into a liquid. Then, these compressed gases might explode and escape toward outside thorough cell voids driven by the rapid pressure drop during the decompression phase. Therefore, these empty spaces that had been filled with gases before the treatment were refilled with water, making a very low gas concentration in the tissue. On the other hand, it was assumed that there was an oxygen gradient from the skin to the core of bamboo shoots after HHP treatment. If these gas-filled intercellular spaces were blocked by water, it could in turn reduce the internal gas diffusivity, which possibly further maintained a low oxygen concentration inside the bamboo shoots after HHP treatment.
**Firmness and TA**

Firmness of fruits and vegetables, as an important physical property to assess the quality of fruits and vegetables, usually declines after harvesting, while the firmness of bamboo shoots increases due to the increase in lignin and crude fiber content during the lignification process. As shown in Figure 4, the firmness of all groups increased during storage, and it was significantly \( P < .05 \) lower in the HHP-treated bamboo shoots than in the untreated shoots. The 400MPa treatment had significantly \( P < .05 \) lower firmness compared to 200 MPa and 300MPa, respectively. After storage for 15 days, the firmness was highest in the control group, at 74.59 N, while the group treated at 400 MPa for 15 min had the lowest firmness, at 51.15 N. On the other hand, the effects of different HHP treatments on the TA in bamboo shoots were shown in Figure 5. The results revealed that TA in bamboo shoots increased along with the storage time. The untreated bamboo shoots presented the highest increase in TA, while the shoots treated at 300MPa showed the lower increase. After 15 days of storage at 25°C, TA content in the control samples was significantly \( P < .05 \) higher than the initial values, which were 0.5797 g kg\(^{-1}\) and 0.1287 g kg\(^{-1}\), respectively. Bamboo shoots treat at 300 MPa for 10 min exhibited the lowest increase and TA was 0.2793 g kg\(^{-1}\) on day 15.

These analytical results show that the HHP treatment could effectively reduce the firmness increase and inhibit the increase of TA content in bamboo shoots during room temperature storage. At low and moderate temperature, HHP treatment significantly inhibited the activities of PPO, POD, PAL, 4-coumarate-coenzyme a ligase (4-Cl) and cinnamyl alcohol dehydrogenase (CAD), the key enzymes of lignin biosynthesis of shelled bamboo shoots. Similar findings were reported by Miao et al., in which, firmness of untreated water bamboo shoots increased by 27.3% after 7 days of storage due to the increased lignin biosynthesis, while through HHP treatment, the firmness tended to increase steadily with a lower rate. During the storage of vegetables or fruits such as mango, loquat and bamboo shoots, a similar increase in firmness has been found, indicating that this was the result of tissue lignification. Moreover, the small change in firmness might be caused by less β–elimination of pectin and activation or retention of pectin methylesterase (PME) activity. On the other hand, the cause of changes in the acidity of fruits and vegetables is usually the occurrence of biochemical reactions such as hydrolysis, oxidation, fermentation, and decomposition. Zhao et al. reported...
that the TA of cucumber juice drinks exhibited an increasing trend during storage, which were in agreement with the present findings. The reason might be that the high pressure damaged the cell wall of the fruits and vegetables, which affected the pH and increased the TA, or might be the acid production of microorganisms. A similar result was reported by Liu et al. in which the TA of wild Lonicera caerulea berries pulps increased under HHP conditions of 500-600 MPa.

**PPO and POD activity**

One of the important factors for the quality decline of postharvest bamboo shoots is browning, which is associated with a series of metabolic processes, among which PPO and POD are the key enzymes of this metabolic pathway. PPO activity of bamboo shoots treated by HHP after 15 d of storage at 25°C is presented in Figure 6. With the prolongation of storage time, the PPO activity of bamboo shoots decreased rapidly at first and then slowly increased, and the change trends in the HHP-treated groups were more significant than those in the control group (P < .05). After 3 days in storage, the PPO activities in control group reached the lowest, at 45.33 U g⁻¹ min⁻¹, while the HHP-treated groups reached the lowest on day 6. While after 15 days of storage, the PPO activity of the control samples was 82.33 U g⁻¹ min⁻¹, which increased to 32.67 U g⁻¹ min⁻¹ in the bamboo shoots treated at 300 MPa for 10 min. Furthermore, as revealed in Figure 7, POD activities in the all groups showed an decreased trend first and increased thereafter, which the trends were similarly to that of PPO activity. In general, POD activities in the HHP-treated groups were significantly (P < .05) lower than that in the untreated group. After 3 days and 6 days in storage, the POD activity in control group and HHP–treated groups reached the lowest, with the highest being that of the control group at 96.33 U g⁻¹ min⁻¹. The treatment of the combination of 300 MPa and 10 min was the most active one in inhibiting the POD activity in bamboo shoots, which POD activity was 103.33 U g⁻¹ min⁻¹ on day 15, while that in the control group was the highest (P < .05), at 184.67 U g⁻¹ min⁻¹.

These results showed that the HHP treatments could significantly inhibit the PPO and POD activity and reduce the extent of browning in bamboo shoots during storage. PPO enzyme plays a vital role in enzymatic browning by oxidizing phenolic compounds to form brown melanin. Therefore, the reduction of PPO enzyme activity is beneficial to reduce the decomposition of total phenols, thereby...
inhibiting the enzymatic browning of bamboo shoots and maintaining the original color of product.\cite{9}

The findings are consistent with the observations of Zhang et al.,\cite{59} who reported that, the PPO activity of strawberry beverage treated with HHP was significantly decreased during storage. The study of Keenan et al.\cite{57} demonstrated that high pressure treatments of 450 MPa resulted in 35% reduction PPO activity compared to fresh fruit smoothies, while samples treated at 600 MPa resulted in 83% reduction PPO activity. In terms of the POD activity, a similar result was reported by them, in which

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**Figure 6.** Effect of HHP treatment on the PPO of bamboo shoots.

**Figure 7.** Effect of HHP treatment on the POD of bamboo shoots.
HHP processing at 400–600 MPa decreased the POD enzyme activity. Similarly, Terefe et al.\cite{60} found that strawberries treated at 600MPa for 10 min resulted in 58% reduction POD activity. Furthermore, several researchers found that the activity of POD in fruits and vegetables increased at low HHP treatment or high HHP treatment, which might be caused by the activation of the POD enzyme or the emergence of new isoenzymes.\cite{61–63}

**Sensory acceptability and color**

Sensory acceptability and color are ones of the most important evaluation indexes of postharvest fruits and vegetables.\cite{64,65} Therefore, the effects of HHP treatment on the sensory acceptability and color (L value) for bamboo shoots were determined. Figure 8 shows the images of bamboo shoots

![Figure 8](image_url)

*Figure 8.* The images of bamboo shoots after HHP treatments (A1-A10: sample images before storage; B1-B10: sample images after 15 days of storage).
after HHP treatments. As can be seen from Figure 8, at the beginning of storage, the bamboo shoots of all treatment groups showed white color. The color of bamboo shoots had change with the prolongation of storage time. After storage for 15 days, the control sample (B1) had severely browning and the bamboo shoots showed tawny color, while the color of samples treat at 300 MPa for 5-15 min (B5-B7) had changed a little. As shown in Figure 9, a decrease in the sensory scores of all treatment groups was observed with the prolongation of storage time, and the down-trend in the control group was more significant than those in the HHP–treated groups ($P < .05$). At the early storage, the sensory scores of the samples in each group were above 9 with no significant
difference between the groups ($P > .05$), while after storage for 12-15 days, some samples appeared sour and astringent with more yellow juice flowing out, and the bamboo shoots became hard due to lignification, which seriously affected their edible quality. The sensory scores of the control group had been reduced from 8.84 points to 2.14 points after storage for 15 days, while the scores in the samples treat at 300 MPa for 10 min had decreased to 7.55, which was much higher than that of the other groups ($P < .05$). On the other hand, the evident color of the product directly affects the edible, thereby affecting the the economic value of the product.\textsuperscript{[66]} Figure 10 shows the effects of different
HHP treatments on color. The results revealed that with the increase of storage time, the L value of bamboo shoots showed an obvious downward trend ($P < .05$). At the beginning of storage, the L values of the HHP-treated samples were significantly ($P < .05$) lower than that of the control group, indicating that the HHP treatment had a certain effect on the color of bamboo shoots due to the promoted leaching out of yellowness-related carotenoids. While after 15 days in storage, L value of the control group was significantly reduced by 36.11% ($P < .05$). The bamboo shoots treated at 300 MPa for 10 min performed higher overall color than that of other treatment groups, which L value was 77.65 at the end of storage.

These results confirm that HHP treatment could effectively inhibited declines in the sensory quality and L* value of bamboo shoots during room temperature storage. The quality of fruits and vegetables after HHP treatment can change during storage due to coexisting chemical reactions,
such as oxidation, and biochemical reactions when endogenous enzymes or microorganisms are not completely inactivated.\textsuperscript{[68]} HHP may affect proteins, but has no effect on low-molecular-weight food components such as amino acids and vitamins, which are responsible for the characteristic appearance and aroma.\textsuperscript{[54]} Therefore, the HHP treatment process retains the organoleptic and nutritional properties of fruits and vegetables, and the quality of treated food is higher.\textsuperscript{[69]} Marszalek et al.\textsuperscript{[70]} reported that taking into account the results of microbiological analyses and tissue enzyme activity, strawberry purée had the high sensory quality under HHP treatment at 500 MPa. Mukhopadhyay et al.\textsuperscript{[54]} also reported similar results, the HHP treatment of 400 MPa for 5 min might minimize the processing of cantaloupe puree with great retention, and maintain the
sensory quality and shelf life of fresh-like fruit. On the other hand, the color of the pressurized fruits and vegetables depends on the chemical reaction related to enzymes such as PPO, POD and PAL which can inhibit browning and the effect of HHP treatment on the stability of the pigments.\cite{71} HHP treatment, at low and moderate temperature, did not break covalent bonds and had limited effect on pigments that affected the color of fruits and vegetables. \cite{68,72,73} Gao et al.\cite{74} suggested

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**Figure 9.** Effect of HHP treatment on the sensory acceptability of bamboo shoots.

**Figure 10.** Effect of HHP treatment on the L value of bamboo shoots.
that strawberry treated by HHP showed better color than samples treated by thermal processing, indicating that HHP processing was an effective method in preserving the quality of fruits and vegetables.

**Microbiological content**

Fresh produce has limited shelf life, while the microbiological content (bacterial count) is one of the important indexes to measure the shelf life and spoilage degree of bamboo shoots. The effect of different combinations of pressure and holding time on the microbial counts of bamboo shoots is shown in Table 2. The results indicated that the total number of bacteria that were present in all samples was below $1.04 \times 10^2$ CFU g$^{-1}$ on day 0. A increase in the total number of bacteria of all treatment groups was observed with the prolongation of storage time, while immediately after HHP treatment, the total number of bacteria was significantly reduced ($P < .05$). When pressure was higher and holding time was longer, the inhibition effects on the total number of bacteria in the HHP-treated groups became stronger. On day 15 of storage, the total number of bacteria in the control group was the highest, which was $3.74 \times 10^5$ CFU g$^{-1}$, while samples treated at 400 MPa for 15 min bacteria counts continued significantly ($P < .05$) lower (84.6 CFU g$^{-1}$) than that of the control.

The HHP treatment could effectively inhibit the increase of microbiological content in bamboo shoots during storage. The findings are consistent with the observations of Patterson et al. $^{[75]}$ who reported that, the microbial total counts increased during storage of carrot juice treated at 500 MPa and 600 MPa for 1 min but it took longer to reach maximum levels compared to the untreated juice, indicating that HHP treatment significantly delayed the recovery and growth of surviving microorganisms. Similarly, Landl et al. $^{[76]}$ found that the microbial counts in apple purée during the 3 weeks of refrigerated storage remained below the detection limit. Krebbers et al. $^{[77]}$ also showed that when tomato puree was treated at 700MPa for 2 minutes, its natural microbiota decreased to a level below the detection limit, and after 24 days of storage, no outgrowth of the microorganisms was observed. Furthermore, the study of Gao et al. $^{[74]}$ demonstrated that the microbial counts of strawberries after HHP treatment were lower than the detection limit before day 30, but increased at day 45. This might be due to the existence of a sublethal injury of fruit cells, which prevents their growth until they recover during storage.

**Conclusion**

The investigation showed the effects of HHP treatment on the quality, enzyme activities and microbiological content in bamboo shoots. The measurement of the weight loss, respiratory intensity and TA content demonstrated the minimal changes under the HHP treatment of 300 MPa for 10 min. The bamboo shoots also displayed the lowest number of changes in the enzyme activities, sensory

| Group          | 0d    | 3     | 6     | 9     | 12    | 15    |
|----------------|-------|-------|-------|-------|-------|-------|
| Control        | $1.04^a \times 10^2$ | $4.34^a \times 10^2$ | $3.14^a \times 10^2$ | $2.87^a \times 10^4$ | $7.94^a \times 10^5$ | $3.74^a \times 10^5$ |
| 200MPa 5 min   | $29.70^b$ | $1.83^b \times 10^2$ | $2.09^b \times 10^2$ | $6.83^b \times 10^3$ | $1.63^b \times 10^4$ | $9.11^b \times 10^4$ |
| 200MPa 10 min  | $19.40^c$ | $86.50^d$ | $1.32^c \times 10^2$ | $7.68^c \times 10^2$ | $4.69^c \times 10^3$ | $3.26^c \times 10^3$ |
| 200MPa 15 min  | $<10^a$ | $9.10^e$ | $1.02^a \times 10^2$ | $4.83^a \times 10^2$ | $2.15^a \times 10^3$ | $7.85^a \times 10^3$ |
| 300MPa 5 min   | $15.60^d$ | $94.10^e$ | $1.68^c \times 10^2$ | $5.25^c \times 10^2$ | $3.94^c \times 10^3$ | $8.91^c \times 10^3$ |
| 300MPa 10 min  | $<10^a$ | $<10^f$ | $17.40^g$ | $74.40^d$ | $1.63^d \times 10^2$ | $3.96^d \times 10^2$ |
| 300MPa 15 min  | $<10^a$ | $<10^f$ | $12.60^d$ | $86.30^d$ | $1.49^d \times 10^2$ | $2.78^d \times 10^2$ |
| 400MPa 5 min   | $<10^a$ | $<10^f$ | $<10^f$ | $39.50^d$ | $96.50^d$ | $2.01^d \times 10^2$ |
| 400MPa 10 min  | $<10^a$ | $<10^f$ | $<10^f$ | $<10^f$ | $68.30^d$ | $1.35^d \times 10^2$ |
| 400MPa 15 min  | $<10^a$ | $<10^f$ | $<10^f$ | $<10^f$ | $26.70^d$ | $84.60^d$ |

Note: Means are averaged values of three replicates. Values within a column with the different letter are significantly different ($P < 0.05$).
acceptability and color. During the storage at room temperature for 15 days, taking into account the results of firmness and microbiological safety, the recommended pressure treatment is that applied at 300 MPa and 10 min. Nevertheless, only the changes of some physical and chemical indexes of bamboo shoots under normal temperature storage after HHP treatment are explored. Combining HHP treatment with different storage temperatures or different preservation methods, and studying the preservation effect of bamboo shoots during storage, especially the changes in nutritional indicators, will be the focus of further research.

Author contributions

Xuanlin Li: Conceptualization, Writing - original draft, Writing review & editing. Yage Xing: Conceptualization, Writing - review & editing, Funding acquisition. Ruru Shui: Methodology, Resources. Xiaotong Cao: Data curation. Ruohan Xu: Data curation. Qinglian Xu: Methodology, Resources. Xiufang Bi: Funding acquisition, Methodology. Xiaocui Liu: Writing - review & editing.

Conflicts of Interest

The authors declare that they have no conflict of interest with any organization regarding the material discussed in this manuscript.

Funding

This work is supported by the Science and technology support program of Sichuan [2017NFP0030, 2018NZ0090, 2019YFN0174 and 2019NZJJ0028], Science and technology support program of Yibin [2018ZSF002], Chengdu Science and Technology Project- key research and development program [2019-YF05-00628-SN and 2019-YF05-00190-SN], Xihua University Graduate Innovation Fund Project [ycj2019082], Innovation Team Construction Program of Sichuan Education Department [15STD0017] and Xihua cup college student science and technology innovation project of Xihua University (2020016).

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