Article
Production of Marinated Chinese Lotus Root Slices Using High-Pressure Processing as an Alternative to Traditional Thermal-and-Soaking Procedure

Lin Yuan 1,2,3,4, Feifei Xu 1,2,3,4,5, Yingying Xu 1,2,3,4, Jihong Wu 1,2,3,4,5 and Fei Lao 1,2,3,4,5,*

1 College of Food Science and Nutritional Engineering, China Agricultural University, Beijing 100083, China
2 National Engineering Research Center for Fruit and Vegetable Processing, Beijing 100083, China
3 Key Laboratory of Fruit and Vegetable Processing, Ministry of Agriculture and Rural Affairs, Beijing 100083, China
4 Beijing Key Laboratory for Food Non-Thermal Processing, Beijing 100083, China
5 Xinghua Industrial Research Centre for Food Science and Human Health, China Agricultural University, Xinghua 225700, China

* Correspondence: fei.lao@cau.edu.cn; Tel.: +86-010-62737464

Abstract: Marinated vegetables are traditional cold dishes with a long history and special flavor in the Chinese deli market. However, the traditional thermal-and-soaking (TS) procedure often results in unreproducible flavor quality properties of marinated vegetables and waste of brine and time in production. A novel green and sustainable technique, high-pressure processing (HPP), has caught the attention of the food industry. In this study, the effects of HPP and TS treatment on the visual, flavor, textural, and microbiological qualities of Chinese marinated lotus root slices were investigated. Compared to the TS products, lighter color, more varieties of volatile compounds, and crunchier texture were detected in the HPP products. Throughout the 4 °C, 25 °C, and 45 °C shelf life challenges, the HPP products retained their original color and crunchiness better than the TS ones, whereas no significant differences were found in total viable counts (TVCs) in the first half of the shelf lives. The Arrhenius model under the first-order reaction of TVC deterioration showed a good fit to the shelf life of the HPP marinated lotus root slices. This study demonstrates that HPP may assist in making the best use of brine in a more time-efficient manner to improve the visual, flavor, and textural quality of traditional Chinese marinated lotus root slices.

Keywords: flavor; color; texture; total viable counts; shelf life; Arrhenius equation

1. Introduction

Marinated vegetables are popular in the Chinese deli market; they are traditional cold dishes with a history that can be traced back to the Qin dynasty (BC221). Unlike food cooked using other methods, marinated vegetables exhibit a delightfully crunchy texture and unique flavor and are abundant in nutrients [1–4]. The most commonly marinated vegetables are lotus root, potato, asparagus, bamboo shoot, and bean curd products. Traditionally, marinated vegetables are boiled for a period of time in brine containing seasonings and spices, such as salt, soy sauce, vinegar, garlic, pepper, and ginger, and then soaked overnight before serving [5]. This dish is conventionally consumed immediately after preparation or after short-term storage under refrigerated conditions. Recently, ready-to-eat marinated vegetables with extended shelf lives have bloomed in the snack market. However, finding a balance between saving brine utilization and stabilizing product flavor and texture quality has been a challenge faced by most manufacturers. Moreover, the industry urgently needs to upgrade the long boiling-and-soaking production cycle, targeting higher time and energy efficiency.

A novel green and sustainable non-thermal sterilization technique, high-pressure processing (HPP), has caught the attention of the food industry in the past decades and has
been reported to be effective in saving water and energy [6,7]. Currently, the application of HPP has been innovatively expanded into areas such as food pretreatment, extraction facilitation, enzyme activity control, and food flavor improvement [8–11]. In marinated foods, HPP has been used mainly for shelf life extension and quality maintenance. Bao et al. [1] found that treatment at 550 MPa for 5 min can effectively inactivate microorganisms in fermented marinated radish with less microstructural damage and better flavor compared to thermal processing. Rodrigues et al. [12] evaluated the impact of HPP on the microbiological properties of marinated beef after refrigerated storage for 14 days and found that HPP led to a reduction of 6 log_{10} colony-forming units (CFU)/g in the two tested microorganisms. Scheinberg et al. [13] reported similar results for bacterial reduction in beef jerky. Moreover, O’Neill et al. [14] reported that HPP at 300, 400, and 500 MPa extended the shelf life of marinated pork chops by 16, 22, and 29 days, respectively. Since the prolongation of shelf life by HPP is mainly due to the inhibition of microbial growth and enzymatic activity [15], the determination of post-HPP food quality changes in storage and prediction of food shelf life based on microbial or enzymatic status is important and would have great practical value.

Several recent studies have developed mathematical models based on quality changes to predict and optimize the shelf life of HPP-treated foods. For example, the polynomial regression model and dimensionless nonlinear model were used to predict the inactivation of Salmonella under different HPP conditions in raw ground chicken meat [16]. The shelf life of human milk treated by HPP, ultraviolet light, and pasteurization was determined at 25 °C and 40 °C using the Arrhenius model based on the percentage of free fatty acids [17]. However, these studies have focused on HPP-treated animal products; similar models for HPP-treated marinated vegetable products are needed as well.

The lotus root (Nelumbo nucifera Gaertn.) belongs to the Nymphaeaceae family and is an aquatic vegetable containing alkaloids, flavonoids, niacin, vitamins, and other bioactive components, thus possessing a high nutritional and medicinal value [18]. The marinated lotus root is a traditional Chinese unfermented ready-to-eat food with high industrial potential. Marinated lotus root slices processed with the traditional thermal-and-soaking (TS) method require a large amount of brine and time; a more advanced green and efficient processing method is in high demand. Hee et al. [19] evaluated the effects of adding different concentrations of beet water extract during storage on the quality characteristics of marinated lotus roots. Li et al. [20] investigated the effects of pulsed electric field pretreatment on the mass transfer kinetics of lotus root slices during marination. Yet, these studies emphasizing novel processing technologies have focused on the safety and taste quality of marinated foods, with little attention paid to volatile aroma substances that directly affect consumer preferences. Investigating the effect of the processing method on the aroma profile of marinated lotus root slices would provide a more comprehensive understanding of the sensory properties of the product.

Therefore, this study aimed to investigate the feasibility of using HPP for the efficient processing of Chinese marinated lotus root slices. The effects of HPP and TS treatment on the flavor, visual, textural, and microbiological qualities of Chinese marinated lotus root slices were investigated. A shelf life model was created to predict the lotus root product performance in different storage temperatures based on the product quality data collected. The information in this study is an important reference to traditional food production modernization, aiming for higher processing efficiency and potential quality improvement.

2. Results and Discussion

2.1. Effect of HPP and TS Processing on the Quality of Marinated Lotus Root Slices

The control sample was excluded from the following experiments because it had a “plastic odor” in the previous sensory evaluation, probably due to the unpleasant aroma release caused by heating the samples packaged with plastic materials [21].
2.1.1. Volatile Compounds

Aroma is an important aspect of the quality evaluation of marinated lotus root slices. The volatile compounds in the blank and marinated lotus root slices are listed in Table 1. In total, 18 volatile compounds were identified in the blank marinated lotus root slices, whereas 32 and 26 volatile compounds were identified in the HPP- and TS-processed marinated lotus root slices, respectively. The blank lotus root has a bland and neutral aroma, and the main volatile compounds such as aldehyds in the blank lotus root are contributed by the soil and water environments [22]. Most of the volatile compounds in the marinated lotus root slices detected in this study were from the spices, herbs, and seasonings in the brine. Higher concentrations of total volatile compounds were detected in the TS samples than in the HPP samples but not significantly. Phenols (e.g., eugenol), heterocyclic compounds (e.g., ethyl maltol), alcohols (e.g., benzyl alcohol), ethers (e.g., cis-anethol), and aldehyds (e.g., benzaldehyde) were the main volatile categories in marinated lotus root slices. These compounds were previously identified as the major contributors to the aromatic components of spices such as clove and fennel [23–26]. Although all other categories of volatile compounds were significantly \((p < 0.05)\) higher in the TS samples than in the HPP samples, the volatile phenols with the highest content were not significantly different \((p > 0.05)\) between the TS and HPP samples. This suggests that HPP can promote the release of volatile compounds at a small amount of brine use to achieve similar aroma quality as TS treatment.

### Table 1. Volatile profiles of HPP and TS marinated lotus root slices.

| No. | Compounds               | Aroma Descriptors ¹ | LRI | Blank   | HPP     | TS      |
|-----|-------------------------|---------------------|-----|---------|---------|---------|
| A1  | 1-Nonanal               | Waxy, rose          | 1393| 12.38 ± 2.17 b | 247.32 ± 97.69 b | 695.10 ± 295.09 a |
| A2  | Benzaldehyde            | Sharp, sweet        | 1510| n.d.    | 776.66 ± 173.01 b | 1209.04 ± 321.12 a |
| A3  | Phenylacetaldhey        | Green, sweet        | 1629| n.d.    | 497.25 ± 330.72 ab | 906.15 ± 5.27 a |
| A4  | 2-Phenyl-2-butenal      | Sweet, narcissus    | 1919| n.d.    | 47.75 ± 5.37 a  | n.d.    |
| A5  | Cinnamaldehyde          | Sweet, spicy        | 2030| n.d.    | 14.07 ± 4.38 a  | n.d.    |
| A6  | Cocal                   | Bitter, cocoa       | 2089| n.d.    | 25.78 ± 6.45 a  | n.d.    |
|     | Subtotal                |                     |     | 12.38 ± 2.17 c | 1608.83 ± 617.62 b | 2810.29 ± 612.47 a |
|     |                        |                     |     |          |          |         |
| B1  | Furfural                | Sweet, woody        | 1457| 15.18 ± 9.63 c | 787.57 ± 118.23 b | 1051.82 ± 98.78 a |
| B2  | 5-Methyl furfural       | Spice, caramel      | 1565| n.d.    | 158.69 ± 39.21 b | 375.96 ± 38.36 a |
| B3  | Acetylpyrazine          | Popcorn, nutty      | 1614| n.d.    | 175.88 ± 62.5 b  | 390.92 ± 36.98 a |
| B4  | Furfuryl alcohol        | Alcoholic, chemical | 1658| n.d.    | 321.83 ± 23.09 a | n.d.    |
| B5  | 2-Acetyl pyrrole        | Musty, nut          | 1958| n.d.    | 332.81 ± 45.26 b | 579.91 ± 44.95 a |
| B6  | Ethyl maltol            | Sweet, caramel      | 1998| n.d.    | 3885.19 ± 860.53 a | 4640.65 ± 963.37 a |
| B7  | 5-(2-Hydroxyethyl)-4-   | Fatty, cooked beef  | 2292| n.d.    | 94.44 ± 18.88 a  | 94.01 ± 17.08 a |
|     | methylthiazole          |                     |     | 15.18 ± 9.63 c | 5757.37 ± 1167.70 b | 7133.27 ± 1199.52 a |
| C1  | Benzyl alcohol          | Floral, rose        | 1865| n.d.    | 2141.2 ± 265.17 b | 2785.97 ± 244.55 a |
| C2  | Phenethyl alcohol       | Floral, rose        | 1898| n.d.    | 740.32 ± 96.60 a  | 843.44 ± 75.53 a |
|     | Subtotal                |                     |     |          | 2881.52 ± 361.77 b | 3629.41 ± 320.08 a |
| D1  | Di-n-decyl ether        |                     | 1199| 0.40 ± 0.11 a  | n.d.    | n.d.    |
| D2  | 4-Alllylanisole         | Sweet, sassafras    | 1662| n.d.    | 235.65 ± 20.07 a  | 252.35 ± 23.80 a |
| D3  | cis-Anethol             | Sweet, anise        | 1818| n.d.    | 1573.04 ± 240.16 a | 1725.51 ± 183.42 a |
| D4  | Methyl eugenol          | Sweet, fresh        | 2010| n.d.    | 488.64 ± 115.99 a | 508.58 ± 41.26 a |
| D5  | Methyl isoeugenol       | Spicy, clove        | 2179| n.d.    | 72.13 ± 12.56 a  | 61.29 ± 25.40 a |
| D6  | Elemicin                | Spice, flower       | 2224| n.d.    | 202.00 ± 53.42 a  | 223.15 ± 16.60 a |
| D7  | Myristicin              | Spicy, warm         | 2252| n.d.    | 307.76 ± 85.43 b  | 571.90 ± 38.19 a |
|     | Subtotal                |                     |     | 0.40 ± 0.11 c | 2879.22 ± 527.63 b | 3342.78 ± 328.67 a |
| E1  | Methoxyacetic acid, 2-  |                     | 1309| 2.58 ± 0.69 a  | n.d.    | n.d.    |
|     | tridecyl ester          |                     |     |          |          |          |
| E2  | Ethyl caprylate         | Fruity, wine        | 1432| n.d.    | 122.46 ± 21.05 b | 291.75 ± 110.42 a |
| E3  | Diethyl succinate       | Mild, fruity        | 1678| n.d.    | 233.60 ± 24.37 b | 343.37 ± 22.89 a |
| E4  | Ethyl myristate         | Sweet, waxy         | 2055| n.d.    | 206.98 ± 34.35 a | n.d.    |
| E5  | Isopropyl myristate     | Oily, fatty         | 2074| 8.11 ± 1.16 a | n.d.    | n.d.    |
Table 1. Cont.

| No. | Compounds                        | Aroma Descriptors 1 | LRI | Concentration (µg/kg) 2 | Blank | HPP   | TS     |
|-----|----------------------------------|---------------------|-----|------------------------|-------|-------|--------|
|     |                                  |                     |     |                        |       |       |        |
|     |                                  |                     |     |                        |       |       |        |
| 1   | Ethyl palmitate                  | Mild, waxy          | 2263|                        | n.d.  | 53.96 | ± 10.99 b |
| 2   | 2-Ethylhexyl salicylate          | Mild, orchid        | 2314|                        | 7.74  | 2.05  a | n.d.   |
| 3   | Dibutyl phthalate                | Faint               | 2698|                        | 6.72  | 2.96  a | n.d.   |
|     |                                  |                     |     |                        | 25.15 | ± 6.86 c | 410.10 ± 56.41 b |
| 4   | Butylated hydroxytoluene         | Phenolic, camphor   | 1912|                        | n.d.  | 63.31 | ± 9.43 a  |
| 5   | Phenol                           | Phenolic, plastic   | 1994|                        | 1.56  | 0.34  c | 44.56 ± 4.15 b |
| 6   | Eugenol                          | Spicy, smoky        | 2156|                        | n.d.  | 9546.86 ± 2096.10 a |
| 7   | 4-Hydroxy-3-methoxystyrene       | Sweet, spicy        | 2185|                        | n.d.  | 48.61 | ± 7.23 a  |
| 8   | 2,4-Di-tert-butylphenol          | Phenolic            | 2333|                        | 19.39 | ± 2.73 a | 494.25 ± 56.39 b |
|     |                                  |                     |     |                        | 53.21 | ± 11.90 a | 10,520.20 ± 2248.45 b |
| 9   | Hexane                           | Waxy                | 1017|                        | 16.17 | ± 2.29 a | n.d.   |
| 10  | Undecane                         |                     | 1081|                        | 16.98 | 2.36  a | n.d.   |
| 11  | Dodecane                         |                     | 1166|                        | 6.84  | 2.07  a | n.d.   |
| 12  | Hexadecane                       |                     | 1641|                        | 6.22  | 0.81  a | n.d.   |
| 13  | Eicosane                         |                     | 1636|                        | 7.00  | 4.37  a | n.d.   |
|     |                                  | Subtotal            |     |                        | 53.21 | 11.90 a | n.d.   |
| 14  | 1-Methylethyl-benzene            |                     | 1138|                        | 15.96 | 6.02  a | n.d.   |
| 15  | DL-Limonene                      |                     | 1173|                        | 3.36  | 0.12  a | 4.91 ± 0.22 a |
| 16  | 6-Methyl-5-hepten-2-one          |                     | 1329|                        | 3.40  | 1.29  a | n.d.   |
| 17  | 1,2,3-Trimethyl-4-[(E)-prop-1-enyl]napththalene | | 2288|                        | 0.76  | 0.02  a | n.d.   |
|     |                                  | Subtotal            |     |                        | 23.48 | 7.45  a | 4.91 ± 0.22 b |
|     |                                  | Total               |     |                        | 150.75 | 41.19 b | 24,062.15 ± 4979.80 a |

1 Reference aroma descriptors from the LRI & Odor Database (http://www.odour.org.uk/, accessed on 14 September 2022).
2 Values are given as mean ± standard deviation (SD; n = 3). n.d., not detected. Different lowercase letters in the same row indicate significant differences at p < 0.05. LRI, linear retention index; HPP, high-pressure processing; TS, thermal-and-soaking.

2.1.2. Color, Texture, and TVC

Table 2 shows the color, texture, and microbiological properties of HPP and TS samples. In contrast to the TS treatment, HPP increased the hardness value of marinated lotus root slices. Basak and Ramaswamy [27] defined instantaneous pressure softening (IPS), i.e., the loss in texture that occurs at the instant of HPP (zero holding time), by measuring and fitting the hardness of HPP-treated fruits and vegetables treated at 100–400 MPa for 5–60 min. The IPS will be recovered to varying degrees with increasing pressurization time. The HPP conditions at 550 MPa with a holding time of 20 min in this study seem to have accomplished this textural recovery. In addition, as reported in previous studies, HPP also increases the hardness of some other marinated products, such as marinated fermented radish [1], marinated beef [11], and calcium-infused baby carrots [28]. This may be due to the aggregation of proteins/peptides [29] or marination-induced changes in cell microstructure, such as membrane permeability, cellular rearrangement, and cell collapse [1,28,30], which alter the effect of HPP on cell volume compression.

The TVC in samples before HPP or TS was 3.98 log_{10} CFU/g and immediately reduced to 1.68 and 1.60 log_{10} CFU/g after HPP and TS treatments, respectively. The main mechanism of action of HPP in microorganisms involves altering cell structure and physiological functions, breaking DNA strands, disrupting cell membrane integrity, inactivating key enzymes, and irreversible denaturation of proteins, resulting in the loss of membrane selectivity [31]. It can be inferred that the bacteria with tolerance to the thermal process may be the thermal-tolerance spores, such as Bacillus and Clostridium [32]. Additionally, the TVC result of HPP samples was not significantly (p > 0.05) different from that of TS.
samples. Therefore, it was speculated that the survivor bacteria after HPP may be the spores because the spores have a high tolerance to HPP [33]. However, according to the shelf-life experiments later in this study, these spores did not have a destructive effect on the quality of marinated lotus root slices.

Table 2. Quality properties of HPP and TS marinated lotus root slices.

|                         | Blank          | HPP            | TS             |
|-------------------------|----------------|----------------|----------------|
| TVC (log_{10} CFU/g)    | 3.98 ± 0.04 a  | 1.68 ± 0.02 b  | 1.60 ± 0.16 b  |
| Hardness (g)            | 14,208.14 ± 1985.80 a | 14,820.45 ± 814.85 a | 11,955.97 ± 1040.45 b |
| pH                      | 6.47 ± 0.02 a  | 5.17 ± 0.03 b  | 4.73 ± 0.04 c  |
| L*                      | 76.35 ± 1.42 a | 51.74 ± 1.52 b | 48.36 ± 0.68 c |
| a*                      | −0.88 ± 0.05 c | 7.58 ± 0.57 b  | 8.48 ± 0.43 a  |
| b*                      | 2.65 ± 0.32 c  | 21.56 ± 1.20 b | 23.95 ± 0.74 a |
| ΔE                      | -              | 32.20 ± 0.45 b | 36.41 ± 0.39 a |

Different lowercase letters in the same row indicate significant differences among the treatments (p < 0.05). HPP, high-pressure processing; TS, thermal-and-soaking; TVC, total viable count; ΔE, total color difference.

The pH of the samples decreased significantly (p < 0.05) after HPP or TS treatment, and the pH of the HPP samples was slightly but significantly (p < 0.05) higher than that of the TS samples, which may be due to the fact that HPP facilitates acidic substance transfer to less of an extent than TS treatment. However, the pH variation of 0.09 is a considerably small change in batch marinated food processing and would not introduce perceivable acidity alteration.

It was observed that HPP and TS processing resulted in a noticeable visual difference in color (Figure 1). Immediately after HPP and TS processing, the L* value of marinated lotus root slices significantly decreased, whereas the a* and b* values increased. The ΔE value of the samples after TS processing was 36.41, which was significantly higher than that of the HPP samples (ΔE = 32.20). This indicates a darker brightness and a redder and more yellowish color of the TS samples compared to the HPP samples. These color changes may be related to cell membrane disruption, thermal denaturation, and the Maillard reaction [34,35].

Figure 1. The appearance of blank (left), HPP (middle), and TS (right) marinated lotus root slices. HPP, high-pressure processing; TS, thermal-and-soaking.

2.2. Effects of HPP and TS Processing on Quality Properties during Different Storage Conditions

2.2.1. Texture Changes

Softening of fruits and vegetables is a process of destruction of the cell structure caused by the breaking of cell walls and dissolution of pectin by the actions of enzymes. During storage, cell rupture due to temperature changes, microbial growth, and a series of biochemical reactions eventually lead to a decrease in product hardness. Therefore, the hardness of fruits and vegetables is often used as an important indicator of quality changes during storage [36,37]. As shown in Figure 2, the hardness of marinated lotus root slices tended to decrease at the three temperatures during storage and finally reached a value of approximately 5000 g at the end of the shelf life. The hardness values of the marinated lotus root slices decreased faster at higher storage temperatures. These findings were consistent with those of previous studies on atemoya [38]. The most important softening process in the HPP or TS process is considered to be the temperature-dependent β-elimination of pectin [39]. In addition, most of the hardness values of HPP marinated lotus root slices were significantly higher (p < 0.05) than those of TS marinated lotus root slices stored at the same temperature (Figure 2). This finding was consistent with the study by Zhang et al. [40].
on yellow peaches in pouches, indicating that HPP could maintain the texture of food. This is due to the release of PME under HPP treatment, which catalyzed the demethylation of high-methylated pectin, and the resulting de-esterified pectin (low-methylated pectin) forms a gel network with divalent ions [41].

![Figure 2](image-url)

**Figure 2.** Changes in hardness of HPP and TS marinated lotus root slices during storage: (A) storage at 45 °C, (B) storage at 25 °C, (C) storage at 4 °C. Different letters indicate significant differences during storage (p < 0.05) for the HPP (uppercase letters) and TS (lowercase letters) marinated lotus root slices. *p < 0.05. HPP, high-pressure processing; TS, thermal-and-soaking.

### 2.2.2. Color Changes

Tables S1 and 3 show the changes in L*, a*, b*, and ΔE values in the HPP and TS marinated lotus root slices during storage at 45 °C, 25 °C, and 4 °C. The quality of the lotus root is mainly reflected by the changes in color, specifically in lightness and yellowness [42]. The L* values of both HPP and TS marinated lotus root slices decreased continuously with storage time, indicating that the color darkened during storage. There was a significant decrease in b* values for marinated lotus root slices during storage, indicating that the yellow hue in marinated lotus root slices degraded significantly. This result was similar to that of a previous study on HPP carrots and thermally processed strawberry puree [30,43]. The ΔE values of marinated lotus root slices significantly increased during storage, indicating that the color quality declined as the storage period increased. The color changes observed in marinated lotus roots during storage may be due to a variety of causes, such as enzymatic or non-enzymatic browning reactions and microbial spoilage [44,45]. However, the ΔE values of the HPP samples were consistently lower than those of the TS samples of the same period at the same storage temperature. Similar results were also found for marinated radish and cloudy kiwifruit juice [1,46]. Therefore, HPP can maintain the original color of the marinated lotus root slices better than the TS process.

In addition, the color of marinated lotus root slices was also affected by storage temperature. HPP and TS samples stored at 4 °C showed more stable color quality than samples stored at 25 °C, with the worst quality being observed in samples stored at 45 °C. The rate of increase in the ΔE values increased with increasing storage temperature, indicating that the rate of browning reactions was accelerated at high storage temperatures. Min et al. [42] reported similar results for freshly cut lotus root. This is because low temperatures reduce enzymatic browning reactions by decreasing enzyme activity and also reduce non-enzymatic browning reactions such as the Maillard reactions and ascorbic acid degradation [35,42,47]. Based on previously published reports, it is unclear whether the effect of storage temperature on the color of HPP samples differs from that of thermally processed samples. Studies performed on orange juice [48] and aloe vera–litchi mixed beverage [49] showed that the color change of HPP samples was more affected by storage temperature than that of thermally processed samples. Opposite results have been reported for clear and cloudy Se-enriched kiwifruit juices [45]. In our study, the color changes of HPP and TS marinated lotus root slices were similarly affected by storage temperature. Therefore, appropriate storage temperatures combined with optimal processing technology help to better preserve the appearance of marinated lotus root slices.
storage temperature on the color of HPP samples differs from that of thermally processed samples. Opposite results have been reported for clear juices [45]. In our study, the color changes of HPP and TS marinated lotus root slices were similarly affected by storage temperature. Therefore, and cloudy Se-enriched kiwifruit juices [45]. In our study, the color changes of HPP and TS marinated lotus root slices were similarly affected by storage temperature. Therefore, and cloudy Se-enriched kiwifruit juices [45]. In our study, the color changes of HPP and TS marinated lotus root slices were similarly affected by storage temperature. Therefore, and cloudy Se-enriched kiwifruit juices [45]. In our study, the color changes of HPP and TS marinated lotus root slices were similarly affected by storage temperature. Therefore, and cloudy Se-enriched kiwifruit juices [45].

2.2.3. TVC Changes

TVC in HPP and TS marinated lotus root slices stored at different temperatures increased at different rates, reaching \(5 \log_{10} \text{CFU/g} \) at 80, 55, and 18 days of storage at 4, 25, and 45 °C, respectively (Figure 3). The sample microbial growth was the fastest when stored at 45 °C and slowest at 4 °C. Except for samples stored at 45 °C on day 18 and at 4 °C on days 35, 55, 70, and 80, there was no significant difference in TVC between HPP and TS marinated lotus root slices (\(p > 0.05\)), indicating that HPP could achieve the same sterilization effect as conventional TS processing in the first half of the shelf lives. Similar results have been reported regarding many fruit and vegetable products [50,51], and HPP is microbiologically safe and the best alternative to thermal processing [52]. However, some studies have also shown that the sterilization effect of HPP is superior [53] or inferior [34] to that of thermal processing, which may be related to pressure, temperature, time, and pH [52].

Table 3. Changes in total color difference of HPP and TS marinated lotus root slices during storage.

| Storage Temperature (°C) | Storage Time (Days) | HPP          | TS           |
|---------------------------|---------------------|--------------|--------------|
|                           | 0                   | 32.20 ± 0.45 j | 36.41 ± 0.39 gh |
|                           | 2                   | 35.34 ± 0.92 hi | 38.08 ± 0.44 cde |
|                           | 4                   | 35.37 ± 0.31 hi | 37.84 ± 0.11 def |
| 45                        | 6                   | 35.18 ± 0.75 i  | 36.76 ± 1.45 fg |
|                           | 9                   | 35.33 ± 0.18 hi | 37.12 ± 0.50 efg |
|                           | 12                  | 37.07 ± 1.14 efg | 39.76 ± 1.68 b |
|                           | 15                  | 38.63 ± 0.20 bcd | 41.38 ± 0.90 a  |
|                           | 18                  | 39.11 ± 0.29 bc | 42.07 ± 0.29 a  |
|                           | 0                   | 32.20 ± 0.45 k  | 36.41 ± 0.39 fgh |
|                           | 4                   | 33.37 ± 1.90 jk | 36.13 ± 0.72 fghi |
|                           | 9                   | 34.40 ± 0.89 ij | 37.52 ± 0.71 efg |
| 25                        | 15                  | 35.65 ± 0.73 hi | 38.01 ± 0.32 def |
|                           | 25                  | 35.88 ± 0.25 ghi | 38.69 ± 1.68 de |
|                           | 35                  | 35.76 ± 0.93 ghi | 41.85 ± 0.50 ab |
|                           | 45                  | 37.69 ± 1.34 efg | 40.88 ± 1.61 bc |
|                           | 55                  | 39.60 ± 0.46 cd | 42.92 ± 1.57 a  |
|                           | 0                   | 32.20 ± 0.45 k  | 36.41 ± 0.39 efg |
|                           | 6                   | 33.08 ± 1.07 jk | 35.28 ± 0.45 ghi |
|                           | 15                  | 33.87 ± 0.84 ijk | 37.66 ± 0.41 def |
| 4                         | 25                  | 34.44 ± 0.79 hij | 38.02 ± 0.15 cde |
|                           | 35                  | 34.49 ± 2.21 ghi | 39.88 ± 0.62 bc |
|                           | 45                  | 35.01 ± 1.59 ghi | 39.82 ± 0.19 bc |
|                           | 55                  | 36.08 ± 2.44 fgh | 40.29 ± 1.56 b  |
|                           | 70                  | 38.60 ± 1.84 bcd | 42.71 ± 1.36 a  |
|                           | 80                  | 40.19 ± 0.25 b  | 42.81 ± 0.38 a  |

Data are expressed as the mean standard deviation (\(n = 4\)). Different lowercase letters in the same column for each storage temperature indicate significant differences at \(p < 0.05\). HPP, high-pressure processing; TS, thermal-and-soaking.

Figure 3. Changes in total viable counts of HPP and TS marinated lotus root slices during storage: (A) storage at 45 °C, (B) storage at 25 °C, (C) storage at 4 °C. Different letters indicate significant differences during storage (\(p < 0.05\)) for the HPP (uppercase letters) and TS (lowercase letters) marinated lotus root slices. * \(p < 0.05\). HPP, high-pressure processing; TS, thermal-and-soaking.
2.3. Shelf Life Prediction Models of HPP Marinated Lotus Root Slices

Zero- and first-order kinetic reaction equations (Equations (1) and (2)) are commonly used to construct food quality reaction kinetic models [55].

Zero − order reaction model : \( C = kt + C_0 \) \hspace{1cm} (1)

First − order reaction model : \( C = C_0 e^{kt} \) \hspace{1cm} (2)

where \( t \) is the storage time (days), \( C \) is the index value of storage time \( t \), \( C_0 \) is the initial value of the index, and \( k \) is the decay rate of the index.

The hardness, TVC, and \( \Delta E \) data of HPP marinated lotus root slices stored at different storage temperatures and times in Figures 2 and 3 and Table 3 were fitted with Equation (1) or (2). The corresponding zero- and first-order reaction rate constants (\( k \)) and the determination coefficients (\( R^2 \)) are listed in Table S2. The average \( R^2 \) values of the kinetic equations for changes in hardness and TVC under the first-order reaction (0.9688 and 0.9900, respectively) were slightly higher than those of the zero-order reaction (0.9524 and 0.9571, respectively), whereas the average \( R^2 \) values of the zero- and first-order reactions for \( \Delta E \) changes were similar (0.9000 and 0.9029, respectively). It has been reported that the changes in the hardness of white button mushrooms and the TVC of grass carp follow the first-order reaction, and the change in \( \Delta E \) of tambaqui fillet follows the zero-order reaction [56–58].

A quantitative description of the relationship between the temperature and the rate of a chemical reaction was further performed using the Arrhenius equation (Equation (3)) [55].

\[
\ln k = \ln k_0 - \frac{E_a}{RT}
\]

where \( k \) is the deterioration rate, \( k_0 \) is the pre-exponential factor, \( E_a \) is the activation energy (J/mol), \( T \) is the storage temperature (K), and \( R \) is the universal gas constant (8.314 J/(mol·K)).

According to Equation (3), the reaction rate constant (\( k \)) for hardness, TVC, and \( \Delta E \) of the HPP marinated lotus root slices in Table S2 were taken logarithmically and linearly fitted to the corresponding 1/T. \( E_a \) and \( k_0 \) were calculated from the slope and intercept of the fitted equations, respectively, as shown in Table 4.

| k0 \( \times 10^6 \) | \( E_a \) \( \times 10^3 \) | Relative Error 1 |
|-----------------|-----------------|-----------------|
| **Hardness**    | Stored at 4 °C | Stored at 25 °C | Stored at 45 °C | Average |
| Zero-order      | 4.50            | 25.00           | 38.90%         | 3.98%   | 6.25% | 16.37% |
| First-order     | 5.57            | 25.33           | 31.03%         | 15.26%  | 1.56% | 15.95% |
| Zero-order      | 6.49            | 27.92           | 15.21%         | 20.13%  | 16.06% | 17.14% |
| First-order     | 1.79            | 27.47           | 16.02%         | 8.07%   | 20.27% | 14.79% |
| **TVC**         | Stored at 4 °C | Stored at 25 °C | Stored at 45 °C | Average |
| Zero-order      | 1.31            | 22.44           | 56.30%         | 18.11%  | 29.44% | 34.62% |
| First-order     | 32.54           | 22.15           | 56.83%         | 21.20%  | 29.12% | 35.71% |
| **\( \Delta E \)** | Stored at 4 °C | Stored at 25 °C | Stored at 45 °C | Average |
| Zero-order      | 1.31            | 22.44           | 56.30%         | 18.11%  | 29.44% | 34.62% |
| First-order     | 32.54           | 22.15           | 56.83%         | 21.20%  | 29.12% | 35.71% |

1 Relative error = \(|\text{Predicted shelf life (day)} - 15|/15) \times 100\%. HPP, high-pressure processing; TS, thermal-and-soaking; TVC, total viable count; \( \Delta E \), total color difference.

By combining the corresponding zero- or first-order kinetic model (Equation (1) or (2)) with the Arrhenius equation (Equation (3)), shelf life prediction models with the variables of temperature (\( T \)) and quality factor (\( C \)) were established, as shown in Equations (4) and (5):

The Arrhenius model under the zero-order reaction:

\[
SL = \frac{|C - C_0|}{k_0 e^{-\frac{E_a}{RT}}}
\]
The Arrhenius model under the first-order reaction:

$$SL = |\ln \frac{C}{C_0}| \frac{k_0 e^{-\frac{E_a}{RT}}}{k_0}$$

where SL is the shelf life (days) of HPP marinated lotus root slices, C is the index value of storage time T, C₀ is the initial value of the index, k₀ is the pre-exponential factor, Eₐ is the activation energy (J/mol), T is the storage temperature (K), and R is the universal gas constant (8.314 J/(mol·K)).

These models could be used to assess the quality of HPP marinated lotus root slices after storage at a given temperature and storage duration, as well as to acquire the real storage time corresponding to a certain quality value.

The k₀ and Eₐ corresponding to hardness, TVC, and ∆E under zero- or first-order reactions in Table 4 were substituted into Equation (4) or (5), respectively, to obtain the shelf life prediction model (models under zero-order reaction are shown as Equations (6a) to (8a), models under first-order reaction are shown as Equations (6b) to (8b)).

The shelf life prediction models of hardness:

$$SL_{\text{hardness}, \text{zero}} = \frac{|C_{\text{hardness}} - C_{\text{hardness}0}|}{4497355 \times e^{-\frac{3007}{T}}}$$

$$SL_{\text{hardness}, \text{first}} = \frac{|\ln \frac{C_{\text{hardness}}}{C_{\text{hardness}0}}|}{556.7 \times e^{-\frac{3046.6}{T}}}$$

The shelf life prediction models of TVC:

$$SL_{\text{TVC}, \text{zero}} = \frac{|C_{\text{TVC}} - C_{\text{TVC}0}|}{6494 \times e^{-\frac{3358.7}{T}}}$$

$$SL_{\text{TVC}, \text{first}} = \frac{|\ln \frac{C_{\text{TVC}}}{C_{\text{TVC}0}}|}{1790 \times e^{-\frac{3303.9}{T}}}$$

The shelf life prediction models of ∆E:

$$SL_{\Delta E, \text{zero}} = \frac{|C_{\Delta E} - C_{\Delta E0}|}{1313 \times e^{-\frac{2699.3}{T}}}$$

$$SL_{\Delta E, \text{first}} = \frac{|\ln \frac{C_{\Delta E}}{C_{\Delta E0}}|}{32.54 \times e^{-\frac{2664.3}{T}}}$$

where SL is the predicted shelf life (days) of HPP marinated lotus root slices; T is the storage temperature (K); C_{\text{hardness}}, C_{\text{TVC}}, and C_{\Delta E} are predicted values of hardness, TVC, and ∆E of HPP marinated lotus root slices after storage for time SL; and C_{\text{hardness}0}, C_{\text{TVC}0}, and C_{\Delta E0} are initial values of hardness, TVC, and ∆E of HPP marinated lotus root slices.

To evaluate the shelf life prediction models of hardness, TVC, and ∆E under zero- and first-order reactions, relative errors between experimental and predicted data were calculated and are presented in Table 4, using day 15 of storage as an example. The shelf life prediction model under first-order reaction (Equation (7b)) could predict storage changes of TVC with the lowest average relative error (14.79%). For the shelf life prediction models under zero-order reactions, the average relative errors between experimental and predicted values of hardness, TVC, and ∆E all exceeded 15%. Additionally, the average relative errors of the shelf life prediction models based on ∆E were the largest (>30%). Therefore, the Arrhenius model under first-order reaction based on TVC (Equation (7b)) was the best-fitted model for modeling the shelf life of HPP marinated lotus root slices during storage at 4–45 °C.
3. Materials and Methods

3.1. Materials and Chemicals

Fresh lotus roots (*Nelumbo nucifera* Gaertn.) segments with an average diameter of 60 mm were provided by Jiangsu Jinsha Foods Co., Ltd. (Xinghua, China). The concentrated spice brine (pH = 4.37, total soluble solids = 16.0° Brix) was supplied by Jiangsu Teweinong Biological Technology Development Co., Ltd. (Xinghua, China). Cyclohexanone (gas chromatography grade) was purchased from ANPEL Laboratory Technologies, Inc. (Shanghai, China). N-Alkane (C7-C30) standards for qualitative analysis were purchased from Sigma (St. Louis, MO, USA). Plate count agar, NaCl, and other analytical-grade reagents were purchased from Beijing Solarbio Science & Technology Co., Ltd., Beijing, China.

3.2. Preparation of Marinated Lotus Root Slices

Lotus roots were cleaned, peeled, sliced into 7 mm thick disks, and blanched with boiling water for 5 min (1:4, w/v). The lotus root slices were cooled in icy water for 10 min and set as a blank group, followed by TS or HPP treatment. According to the instructions for the concentrated spice brine provided by the manufacturer, water and concentrated brine (4:1, w/w) were added to a crock and boiled. The dreg-removed brine was used to marinate the lotus root slices.

Samples (100.0 ± 0.1 g) for TS treatment were boiled in boiling brine (100 °C, 100.0 g) for 20 min, soaked for 5 h in the brine without heating (25 °C), and vacuum-packed without brine using a vacuum-packing machine (Deli Group Co., Ltd., Ningbo, China) in a clear polyethylene retort pouch (15 cm × 22 cm).

Samples (100.0 ± 0.1 g) for HPP treatment were vacuum-packed into a retort pouch containing 15 g of brine, subjected to a high hydrostatic pressure pressurization unit (CQC30L-600, Suyuanzhongtian Scientific Co., Ltd., Beijing, China), and treated at 550 MPa for 20 min at room temperature (approximately 25 °C). Distilled water was used as the pressure-transmitting fluid, and the pressurization rate was approximately 120 MPa/min. Decompression (<3 s) was performed immediately after the treatment to minimize adiabatic heating. The treatment time did not include the pressure increase or release time.

Lotus root slices (100.0 ± 0.1 g) vacuum packed with 15 g of brine were boiled at 100 °C for 20 min and left at 25 °C for 5 h and set as the control group.

3.3. Quality Evaluation

3.3.1. Analysis of Volatile Compounds

- **Extraction of volatile compounds**

  The extraction of volatile compounds was performed following the method described by Shen et al. [59] using solid-phase microextraction (SPME), with minor modifications. Chopped samples (2.5 g) were homogenized and transferred into a headspace bottle (20 mL, ANPEL Laboratory Technologies Inc., Shanghai, China) containing 50 µL of 1000 times diluted cyclohexanone as an internal standard. The bottles were sealed using a PTFE-silicone septum and equilibrated at 50 °C for 15 min with agitation. Next, a 50/30 µm divinylbenzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS) SPME fiber (Supelco, Bellefonte, PA, USA) was exposed to the headspace of the samples for 40 min at the same temperature without stirring. Finally, the fiber was withdrawn and introduced into the GC injector at 250 °C for 5 min.

- **Gas chromatography–mass spectrometry (GC-MS) analysis**

  GC-MS measurements were conducted following the method of previous studies [60], with minor modifications, using an Agilent 7890 gas chromatography system (Agilent Technologies, Santa Clara, CA, USA) equipped with an Agilent 5975C series mass spectrometer. The volatile compounds were isolated with a DB-WAX (30 m × 320 µm i.d. × 0.25 µm) fused silica capillary column (Agilent Technologies). Helium (purity ≥ 99.999%) was used as the carrier gas at a rate of 1.0 mL/min constant flow. The oven temperature was maintained at 40 °C for 12 min, increased at a rate of 3 °C/min to 108 °C, and then maintained
at 108 °C for 2 min, followed by an increase to 250 °C at a rate of 5 °C/min for 5 min. Mass spectrometry was performed in the electron impact mode of 70 eV with a scan range of 450–550 m/z.

- **Identification and quantification analysis**

  The volatile compounds in HPP and TS marinated lotus root slices were identified by comparing sample mass spectra with those of the standard NIST12 database and by comparing the calculated linear retention indices (LRIs) with the open-access data of the NIST WebBook. The LRIs of volatile compounds were calculated using the retention times (RTs) of a liquid injection of 1 µL of C7-C30 n-alkane standards obtained using the same GC-MS temperature program. A difference value below 20 between the calculated LRI values and those from the NIST Chemistry WebBook (https://webbook.nist.gov/chemistry/ (accessed on 31 October 2021)) was considered acceptable. LRI was calculated using the following equation:

  \[
  \text{LRI} = 100N + \frac{100(n_{Ra} - n_{RN})}{t_{R(N+n)} - t_{RN}}
  \]

  where N is the number of carbon atoms of n-alkanes immediately before the RT of the compound, n is the difference in the number of carbon atoms of n-alkanes immediately before and after the RT of the compound, t_{Ra} is the RT of the compound, t_{RN} is the RT of n-alkanes immediately before the compound, and t_{R(N+n)} is the RT of n-alkanes immediately after the compound.

  Quantification of volatile compounds in HPP and TS marinated lotus root slices was performed using cyclohexanone as an internal standard. The peak areas were normalized to the cyclohexanone added to each sample. The concentrations of the identified compounds were calculated from the ratio of the peak area to that of the internal standard.

3.3.2. **Determination of pH and Hardness**

  Marinated lotus root slices were removed from the pouch and homogenized (FSH-2A, Fangke Instrument Co., Ltd., Changzhou, China). The pH of the mixture was measured at 25 °C using a Crison basic 20 pH meter (Crison, Spain).

  Texture is an important quality indicator of marinated vegetables, and in this study, hardness was chosen as an indicator of the texture parameter [2,61]. Hardness measurements were performed within 1 h after HPP or TS treatment using a TAXT plus texture analyzer (Stable Micro Systems, Surrey, England) as described by Dong et al. [62], with some modifications. The compression force at 30% strain was obtained using a cylindrical flat probe (50 mm diameter, aluminum). The sample was cut into cubes (1.0 cm × 1.0 cm × 0.7 cm); placed on the platform with the square side face up; and measured with a 5 g trigger at 1, 1, and 5 mm/s of pre-speed, test speed, and post-speed, respectively. The hardness of each sample was defined as the peak force at a strain of 30%.

3.3.3. **Measurements of Color**

  The color of the marinated lotus root slices was measured at room temperature (approximately 25 °C) using a color difference meter (ColorQuest XE, Hunter Associated Laboratory Inc., USA) in the reflectance mode immediately after opening the pouches. The light source was set to D65 with a 0.375-inch observation aperture and a 10° observation angle. The chromometer was calibrated using a white standard before the samples were measured. The color was recorded in units of L*, a*, and b* uniform color spaces. L* indicates lightness, the a* scale ranges from negative values for green to positive values for red, and the b* scale ranges from negative values for blue to positive values for yellow. The total color difference (ΔE) was calculated using the following equation:

  \[
  \Delta E = \sqrt[3]{(L^* - L^*_0)^2 + (a^* - a^*_0)^2 + (b^* - b^*_0)^2}
  \]

  where L^*_0, a^*_0, and b^*_0 are the values for the blank lotus root slices.
3.3.4. Determination of TVC

The number of microorganisms in the marinated lotus root slices was determined using the total plate counting method. Marinated lotus root slices (10.0 g) were chopped and homogenized with 90.0 mL sterile 0.85% NaCl solution; the sample was then 10-fold serially diluted with sterile 0.85% NaCl solution, and 1.0 mL of each dilution was plated onto a nutrient agar plate (20.0 mL). The nutrient agar was used for detecting TVC after incubation at 37 °C for 48 h. The microorganism numbers of the samples were enumerated as \(\log_{10}\) of CFU/g.

3.4. Storage Conditions

The packaged HPP (including 100.0 g of lotus root slices and 15.0 g of brine) and TS (including 100.0 g of lotus root slices without brine) marinated lotus root slices were stored at 4, 25, and 45 °C in an incubator (PHX, Ningbo Laifu Technology Co., Ltd., Ningbo, China) until the sample microbial load exceeded the usually accepted limit of 5 \(\log_{10}\) CFU/g [63]. Samples were analyzed on days 0, 6, 15, 25, 35, 45, 55, 70, and 80 at 4 °C; 0, 4, 9, 15, 25, 35, 45, and 55 at 25 °C; and 0, 2, 4, 6, 9, 12, 15, and 18 at 45 °C to determine chemical and microbiological quality changes during storage. Each time, three pouches of marinated lotus root slices from each batch were collected for duplicate measurements.

3.5. Statistics Analysis

All results are presented as the average ± standard deviation (SD). One-way analysis of variance (ANOVA) and Duncan’s multiple range test were conducted to determine significant differences between samples using SPSS (version 25.0; Chicago, IL, USA), where the significance level was set at \(p < 0.05\). GraphPad Prism 8.0 (San Diego, CA, USA) and Origin 2019 software (Northampton, MA, USA) were used for data plotting.

4. Conclusions

In this study, HPP demonstrated the potential to improve marinated food quality while resulting in brine savings of approximately 85%. Both HPP (550 MPa, 20 min) and traditional TS (100 °C, 20 min; 25 °C, 5 h) marinated lotus root slices showed a decrease in TVC on day 0 and slight variations in the visual appeal, texture, and aroma qualities. During storage at different temperatures, HPP and TS samples exhibited similar microbiological safety. At the end of the storage period, less deterioration in hardness and color was observed in HPP marinated lotus root slices than in TS samples. The Arrhenius model under first-order reaction based on TVC was the best-fitted model for modeling the shelf life of HPP marinated lotus root slices during storage at 4–45 °C. Therefore, HPP can be an alternative and efficient option to extend the shelf life of marinated lotus root slices with less effect on the quality properties and less brine waste.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/molecules27196506/s1, Table S1: Changes in color of HPP and TS marinated lotus root slices during storage. Table S2: Reaction rate constant k and determination coefficient \(R^2\) for zero- and first-order regression of HPP-treated marinated lotus root slices at different temperatures.

Author Contributions: Conceptualization, L.Y. and F.L.; methodology, F.X.; data curation, L.Y. and F.X.; writing—original draft preparation, L.Y.; writing—review and editing, Y.X. and F.L.; project administration, J.W. and F.L.; funding acquisition, J.W. and F.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Open Fund of the Xinghua Industrial Research Centre for Food Science and Human Health, China, grant number 201907, and the 2115 Talent Development Program of China Agricultural University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.
Data Availability Statement: Data is contained within the article or Supplementary Material.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Bao, R.; Fan, A.; Hu, X.; Liao, X.; Chen, F. Effects of high pressure processing on the quality of pickled radish during refrigerated storage. *Innov. Food Sci. Emerg. Technol.* 2016, 38, 206–212. [CrossRef]
2. Zhang, F.; Zheng, J.; Zhong, J.; Chen, G.; Kan, J. Kinetics of texture change of bamboo shoots during pickling process. *J. Food Process Eng.* 2017, 40, e12369. [CrossRef]
3. Casado, F.J.; Lopez, A.; Rejano, L.; Sanchez, A.H.; Montano, A. Nutritional composition of commercial pickled garlic. *Eur. Food Res. Technol.* 2004, 219, 355–359. [CrossRef]
4. Kumakura, K.; Kato, R.; Kobayashi, T.; Sekiguchi, A.; Kimura, N.; Takahashi, H.; Takahashi, A.; Matsuoka, H. Nutritional content and health benefits of sun-dried and salt-aged radish (*takuan-zuke*). *Food Chem.* 2017, 231, 33–41. [CrossRef] [PubMed]
5. Ghnimi, S.; Guizani, N. Vegetable Fermentation and Pickling. In *Handbook of Vegetables and Vegetable Processing*; Wiley: New York, NY, USA, 2011; pp. 351–367.
6. Milani, E.A.; Ramsey, J.G.; Silva, F.V.M. High pressure processing and thermosonication of beer: Comparing the energy requirements and *Saccharomyces cerevisiae* ascospores inactivation with thermal processing and modeling. *J. Food Eng.* 2016, 181, 35–41. [CrossRef]
7. Munoz, I.; Baptista de Sousa, D.A.; Dolors Guardia, M.; Rodriguez, C.J.; Nunes, M.L.; Oliveira, H.; Cunha, S.C.; Casal, S.; Marques, A.; Cabado, A.G. Comparison of different technologies (conventional thermal processing, radiofrequency heating and high-pressure processing) in combination with thermal solar energy for high quality and sustainable fish soup pasteurization. *Food Bioproc. Technol.* 2022, 15, 795–805. [CrossRef]
8. Wu, S.; Tong, Y.; Zhang, C.; Zhao, W.; Lyu, X.; Shao, Y.; Yang, R. High pressure processing pretreatment of Chinese mitten crab (*Eriocheir sinensis*) for quality attributes assessment. *Innov. Food Sci. Emerg. Technol.* 2021, 73, 102793. [CrossRef]
9. Irna, C.; Jaswir, I; Othman, R.; Jimat, D.N. Antioxidant and antimicrobial activities of astaxanthin from Penaeus monodon in comparison between chemical extraction and high pressure processing (HPP). *Int. Food Res. J.* 2017, 24, S508–S513.
10. Li, R.; Hou, Z.; Zou, H.; Wang, Y.; Liao, X. Inactivation kinetics, structural, and morphological modification of mango soluble acid invertase by high pressure processing combined with mild temperatures. *Food Res. Int.* 2018, 105, 845–852. [CrossRef]
11. Zhang, Y.; Zhang, Z.H.; He, R.; Xu, R.; Zhang, L.; Gao, X. Improving soy sauce aroma using high hydrostatic pressure and the preliminary mechanism. *Foods* 2022, 11, 2190. [CrossRef]
12. Rodrigues, I.; Trindade, M.A.; Caramit, F.R.; Candogan, K.; Pokhrel, P.R.; Barbosa-Canovas, G.V. Effect of high pressure processing on physicochemical and microbiological properties of marinated beef with reduced sodium content. *Innov. Food Sci. Emerg. Technol.* 2016, 38, 328–333. [CrossRef]
13. Scheinberg, J.A.; Svoboda, A.L.; Cutter, C.N. High-pressure processing and boiling water treatments for reducing *Listeria monocytogenes, Escherichia coli* O157:H7, *Salmonella* spp., and *Staphylococcus aureus* during beef jerky processing. *Food Control* 2014, 39, 105–110. [CrossRef]
14. O’Neill, C.M.; Cruz-Romero, M.C.; Duffy, G.; Kerry, J.P. Improving marinade absorption and shelf life of vacuum packed marinated pork chops through the application of high pressure processing as a hurdle. *Food Packag. Shelf Life* 2019, 21, 100350. [CrossRef]
15. Sehrawat, R.; Kaur, B.P.; Nema, P.K.; Tewari, S.; Kumar, L. Microbial inactivation by high pressure processing: Principle, mechanism and factors responsible. *Food Sci. Biotechnol.* 2021, 30, 19–35. [CrossRef]
16. Chai, H.-E.; Sheen, S. Effect of high pressure processing, allyl isothiocyanate, and acetic acid stresses on *Salmonella* survivals, storage, and appearance color in raw ground chicken meat. *Food Control* 2021, 123, 107784. [CrossRef]
17. Aguilar Uscanga, B.R.; Solis Pacheco, J.R.; Ragazzo-Sanchez, J.A.; Cavazos Garduno, A.; Muro Valdez, J.C.; Rodriguez Arreola, A.; Serrano Nino, J.C. Assessment of the accelerated shelf life of human milk dehydrated by aspersion and treated by UV, high pressures, and pasteurization. *J. Food Qual.* 2021, 6688266. [CrossRef]
18. Chiang, P.Y.; Luo, Y.Y. Effects of pressurized cooking on the relationship between the chemical compositions and texture changes of lotus root (*Nelumbo nucifera* Gaertn.). *Chem. Food. 2007, 105, 480–484. [CrossRef]
19. Hee, P.B.; Ryae, J.E.; Cho, H.S. Changes in the quality characteristics of lotus root pickle with beet extract during storage. *J. Korean Soc. Food Sci. Nutr.* 2009, 38, 1124–1129.
20. Li, J.; Shi, J.; Wang, T.; Huang, X.; Zou, X.; Li, Z.; Zhang, D.; Zhang, W.; Xu, Y. Effects of pulsed electric field pretreatment on mass transfer kinetics of pickled lotus root (*Nelumbo nucifera* Gaertn.). *LWT-Food Sci. Technol.* 2021, 151, 112205. [CrossRef]
21. Sanders, R.A.; Zyyazik, D.V.; Morsch, T.R.; Zimmerman, S.P.; Searles, P.M.; Strothers, M.A.; Eberhart, B.L.; Woo, A.K. Identification of 8-nonenal as an important contributor to “plastic” off-odor in polyethylene packaging. *J. Agric. Food Chem.* 2005, 53, 1713–1716. [CrossRef]
22. Li, S.; Li, X.; Lamikanra, O.; Luo, Q.; Liu, Z.; Yang, J. Effect of cooking on physicochemical properties and volatile compounds in lotus root (*Nelumbo nucifera* Gaertn.). *Chem. Food. 2017, 216, 316–323. [CrossRef] [PubMed]
23. Idowu, S.; Adekoya, A.E.; Igiehon, O.O.; Idowu, A.T. Clove (*Syzygium aromaticum*) spices: A review on their bioactivities, current use, and potential application in dairy products. *J. Food Meas. Charact.* 2021, 15, 3419–3435. [CrossRef]
24. Zhu, H.B.; Fan, Y.C.; Qian, Y.L.; Tang, H.F.; Ruan, Z.; Liu, D.H.; Wang, H. Determination of spices in food samples by ionic liquid aqueous solution extraction and ion chromatography. Chin. Chem. Lett. 2014, 25, 465–468. [CrossRef]

25. Wu, J.; Xu, Y.; Xiang, Z. Chemical Composition of Essential Oil from the Leaves of Two Species of BaiJiangCao, Patrinia Scabiosae-folia Fisch and Patrinia Villosa (Thunb.). In Proceedings of the 5th International Conference on Energy and Environmental Protection (ICEEP), Shenzhen, China, 17–18 September 2016; pp. 482–487.

26. Jerkovic, I.; Mastelic, J.; Milos, M. The effect of air-drying on glycosidically bound volatiles from seasonally collected origano (Origanum vulgare ssp hirtum) from Croatia. Nahr. Food 2001, 45, 47–49. [CrossRef]

27. Basak, S.; Ramaswamy, H.S. Effect of high pressure processing on the texture of selected fruits and vegetables. J. Texture Stud. 1998, 29, 587–601. [CrossRef]

28. Gwanpua, S.G.; Van Buggenhout, S.; Verlinden, B.E.; Christiaens, S.; Shpigelman, A.; Vicent, V.; Kermani, Z.J.; Nicolai, B.M.; Guerrero-Beltran, J.A.; Barbosa-Canovas, G.; Swanson, B.G. High hydrostatic pressure processing of fruit and vegetable products. In Innov. Food Sci. Emerg. Technol. 2019, 22, 11–21. [CrossRef]

29. Olivier, S.A.; Smith, R.; Bull, M.K.; Chapman, B.; Knoerzer, K. Apparatus for the simultaneous processing of mesophilic spores by microbial stability, drip loss, lipid and protein oxidation, and sensory properties. Innov. Food Sci. Emerg. Technol. 2014, 20, 49–55. [CrossRef]

30. Giang, Q.; Bari, D.; Lille, M.; Van Loey, A.; Hendrickx, M.; Geeraerd, A. Pectin modifications and the role of pectin-degrading enzymes during postharvest softening of Jonagold apples. Food Chem. 2014, 158, 283–291. [CrossRef]

31. Jerkovic, I.; Mastelic, J.; Milos, M. The effect of air-drying on glycosidically bound volatiles from seasonally collected origano (Origanum vulgare ssp hirtum) from Croatia. Nahr. Food 2001, 45, 47–49. [CrossRef]

32. Araya, X.I.T.; Smale, N.; Zabaras, D.; Winley, E.; Forde, C.; Stewart, C.M.; Mawson, A.J. Sensory perception and quality attributes of high pressure processed carrots in comparison to raw, sous-vide and cooked carrots. Innov. Food Sci. Emerg. Technol. 2009, 10, 420–433. [CrossRef]

33. Sun, L.C.; Sridhar, K.; Tsai, P.J.; Chumpookam, J.; Shiesh, C.C. Effect of ripening and storage temperatures on quality of atemoya (A. squamosa Mill. x A. squamosa L.) fruit. Acta Hortic. 2014, 158, 283–291. [CrossRef]

34. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

35. Yi, J.; Kebede, B.T.; Doan Ngoc Hai, D.; Buve, C.; Grauwet, T.; Van Loey, A.; Hu, X.; Hendrickx, M. Quality change during high pressure processing and thermal processing of cloudy apple juice. LWT-Food Sci. Technol. 2017, 75, 85–92. [CrossRef]

36. Araya, X.I.T.; Smale, N.; Zabaras, D.; Winley, E.; Forde, C.; Stewart, C.M.; Mawson, A.J. Sensory perception and quality attributes of high pressure processed carrots in comparison to raw, sous-vide and cooked carrots. Innov. Food Sci. Emerg. Technol. 2009, 10, 420–433. [CrossRef]

37. Jerkovic, I.; Mastelic, J.; Milos, M. The effect of air-drying on glycosidically bound volatiles from seasonally collected origano (Origanum vulgare ssp hirtum) from Croatia. Nahr. Food 2001, 45, 47–49. [CrossRef]

38. Zhu, H.B.; Fan, Y.C.; Qian, Y.L.; Tang, H.F.; Ruan, Z.; Liu, D.H.; Wang, H. Determination of spices in food samples by ionic liquid aqueous solution extraction and ion chromatography. Chin. Chem. Lett. 2014, 25, 465–468. [CrossRef]

39. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

40. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

41. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

42. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

43. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

44. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

45. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

46. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

47. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

48. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

49. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]

50. Oey, I.; Lille, M.; Van Loey, A.; Hendrickx, M. Effect of high-pressure processing on colour, texture and flavour of strawberry puree: Part I: Influence of process variables on calcium infusion and hardness of the baby carrots. Food Bioproc. Technol. 2011, 12, 255–266. [CrossRef]
50. García-Parra, J.; González-Cembrino, F.; Delgado, J.; Lozano, M.; Hernández, T.; Ramírez, R. Effect of thermal and high-pressure processing on the nutritional value and quality attributes of a nectarine purée with industrial origin during the refrigerated storage. *J. Food Sci.* 2011, 76, C618–C625. [CrossRef]

51. Liu, F.; Zhang, X.; Zhao, L.; Wang, Y.; Liao, X. Potential of high-pressure processing and high-temperature/short-time thermal processing on microbial, physicochemical and sensory assurance of clear cucumber juice. *Innov. Food Sci. Emerg. Technol.* 2016, 34, 51–58. [CrossRef]

52. Roobab, U.; Aadil, R.M.; Madni, G.M.; Bekhit, A.E.D. The impact of nonthermal technologies on the microbiological quality of juices: A review. *Compr. Rev. Food Sci. Food Saf.* 2018, 17, 437–457. [CrossRef]

53. Delgado-Adamez, J.; Franco, M.N.; Sanchez, J.; De Miguel, C.; Ramírez, M.R.; Martin-Vertedor, D. Comparative effect of high pressure processing and traditional thermal treatment on the physicochemical, microbiology, and sensory analysis of olive jam. *Grasas Aceites* 2013, 64, 432–441. [CrossRef]

54. Hurtado, A.; Dolors Guardia, M.; Picouet, P.; Jofre, A.; Maria Ros, J.; Banon, S. Stabilization of red fruit-based smoothies by high-pressure processing. Part. A. Effects on microbial growth, enzyme activity, antioxidant capacity and physical stability. *J. Sci. Food Agric.* 2017, 97, 770–776. [CrossRef] [PubMed]

55. van Boekel, M.A.J.S. Kinetic modeling of food quality: A critical review. *Compr. Rev. Food Sci. Food Saf.* 2008, 7, 144–158. [CrossRef]

56. Song, Y.; Hu, Q.; Wu, Y.; Pei, F.; Kimatu, B.M.; Su, A.; Yang, W. Storage time assessment and shelf-life prediction models for postharvest Agaricus bisporus. *LWT-Food Sci. Technol.* 2019, 101, 360–365. [CrossRef]

57. Zhang, L.; Li, X.; Lu, W.; Shen, H.; Luo, Y. Quality predictive models of grass carp (*Ctenopharyngodon idellus*) at different temperatures during storage. *Food Control* 2011, 22, 1197–1202. [CrossRef]

58. Ramos, F.C.P.; Ribeiro, S.C.A.; Peixoto Joele, M.R.S.; Sousa, C.L.; Lourenco, L.F.H. Kinetic modeling to study the quality of tambaqui (*Colossoma macropomum*) sous vide during storage at different temperatures. *J. Food Sci. Technol.* 2017, 54, 2452–2463. [CrossRef]

59. Shen, Q.; Cheng, H.; Pu, Y.F.; Ren, S.J.; Hu, L.L.; Chen, J.C.; Ye, X.Q.; Liu, D.H. Characterization of volatile compounds in pickled and dried mustard (*Brassica juncea*, Coss.) using optimal HS-SPME-GC-MS. *Cyta J. Food* 2018, 16, 331–339. [CrossRef]

60. Yao, Y.; Fan, S.; Fan, G.; Dong, L.; Ren, J.; Zhu, Y. Evaluation of volatile profile of Sichuan dongcai, a traditional salted vegetable, by SPME-GC-MS and E-nose. *LWT-Food Sci. Technol.* 2015, 64, 528–535. [CrossRef]

61. Yang, Z.; Duan, X.; Yang, J.; Wang, H.; Liu, F.; Xu, X.; Pan, S. Effects of high hydrostatic pressure and thermal treatment on texture properties of pickled kohlrabi. *LWT-Food Sci. Technol.* 2022, 157, 113078. [CrossRef]

62. Dong, P.; Kong, M.; Yao, J.; Zhang, Y.; Liao, X.; Hu, X.; Zhang, Y. The effect of high hydrostatic pressure on the microbiological quality and physicochemical properties of lotus root during refrigerated storage. *Innov. Food Sci. Emerg. Technol.* 2013, 19, 79–84. [CrossRef]

63. Yi, T.; Fang, W.; Xie, X.; Yuan, B.; Lu, M.; Xu, C. High pressure processing (HPP) improved safety and quality of emerging aronia berry juice: A pilot scale shelf life study. *J. Food Sci. Technol.* 2022, 59, 755–767. [CrossRef] [PubMed]