Sustainable Food Technology

COMMUNICATION

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Cite this: *Sustainable Food Technol.*, 2025, **3**, 1309

Received 24th March 2025
Accepted 28th June 2025

DOI: 10.1039/d5fb00108k

rsc.li/susfoodtech

Effect of vacuum microwave drying pretreatment on the quality characteristics and textural structure of new paocai raw materials

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Suitable storage of the fresh raw vegetables used in the naturally fermented Sichuan pickle, paocai, poses a challenge for commercial producers. The objective of this study was to investigate the effects of microwave–vacuum drying at different water loss rates (30%, 35%, 40%, 45%, 50% and 55%) on the quality preservation of new-paocai raw materials. The results showed that as the rate of water loss increased with this technique, the rehydration rate increased and the hardness, chewiness and viscosity of the raw vegetables tended to decrease. At the maximum water loss rate of 55%, the hardness, chewiness and viscosity of the radish slices decreased to 339.75 g, 238.84 g and 263.53 g, respectively; the highest rehydration ratio was 1.96% and, in comparison with the untreated samples (61.51 μg g^{-1}), the vitamin C content decreased to 9.83 μg g^{-1} corresponding to a loss rate of 84.02%. When water loss exceeded 45% in the radish slices, the color change and destruction of the shape structure were obvious, the sensory properties showed a downward trend, and the springiness reached a maximum value of 0.91 g, exceeding the untreated sample's value of 0.85 g. These experimental results ascertained that paocai raw materials display high rehydration rates, excellent texture, nutrient retention and optimal quality at a microwave–vacuum drying water loss rate of 45%. The findings of this study provide a foundation for subsequent experiments and a theoretical basis for improvements to the industrial production of paocai.

Sustainability spotlight

This study advances SDG 2 and SDG 12 by developing a low-salt, energy-efficient vacuum–microwave drying pretreatment for paocai raw materials. Compared with traditional paocai methods, the technology reduces salt use, minimizes high-salt wastewater discharge, and reduces drying energy consumption by reducing treatment time. By preserving 84% of vitamin C under optimal drying conditions (45% water loss), the method enhances nutritional quality while extending shelf life, supporting sustainable food preservation practices. The findings directly contribute to healthier, resource-efficient pickle production, aligning with consumer demand for environmentally responsible fermented foods.

1 Introduction

Paocai, a typical representation of the ancient Chinese art of vegetable pickling, is a product of spontaneous fermentation of lactic acid in salt water.[1] Since paocai is made from fresh vegetables, its production is limited by a variety of environmental factors, including season, temperature and humidity. In making traditional paocai, enterprises typically extend the vegetable storage period by curing the raw materials with high salt, to achieve a long-term supply. However, this method not only requires extensive vegetable storage areas but also produces a lot of high salinity wastewater, which, if left untreated, can disrupt conventional biochemical treatment systems and lead to serious environmental pollution.[2,3] The problem of highly saline wastewater is exacerbated by the lack of efficient treatment technologies, limited comprehensive utilization, high treatment costs, and significant resource waste. Other challenges experienced by traditional paocai producers using salt storage to preserve their raw vegetable materials include low productivity, higher production costs, potential instability of flavor substances and uncertainty in microbial species.

In order to reduce these problems, the researchers have designed a new-paocai production technology to effectively solve these problems. First, the fresh vegetables are dehydrated by vacuum–microwave drying, followed by the separate fermentation of the flavor brine. Finally, the dehydrated raw material and flavor brine yield the new-paocai product through synergistic penetration under high pressure. In the production of new-paocai, the drying of raw materials is a fundamental step and plays an important role in product quality. Drying not only extends the shelf life of agricultural products but also reduces

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their volume and weight, thus reducing the storage and transportation space required for agricultural products.[4,5] Many industrial drying techniques have now been developed, but the drying method may adversely impact the quality characteristics of fruits and vegetables.[6] Therefore, it is important to choose a suitable drying method for kimchi raw materials. Microwave–vacuum drying technology is a relatively new technique combining vacuum drying and microwave drying. The intensive heating from the microwave and the low boiling point generated by the vacuum dry the material at a relatively low temperature over a short duration, maintaining a high level of the vegetable's original nutritional content and its sensory quality.[7] Consequently, the microwave–vacuum drying technique has quickly gained popularity in the food industry.

Compared with traditional hot air drying, vacuum–microwave drying is characterized by a short drying time, high drying rate and high rehydration capacity.[8] For example, changes in the color and nutritional value of the sample are inevitable after hot air drying, which tends to cause skin browning, hardening, wrinkling and significant quality loss.[9] Li *et al.* found that microwave–vacuum drying was able to preserve the living probiotics, bioactive components, and antioxidant capacities of fermented napa cabbages better than hot-air drying.[10] In a study on strawberry dehydration, microwave–vacuum drying resulted in products with less degradation of anthocyanins, flavanols and ascorbic acid in comparison to those produced *via* convective drying.[11] Microwave–vacuum drying has already been successfully applied to reduce the moisture content of numerous vegetables and fruits, including blueberries,[12] carrots,[13] cranberries[14] and purple cabbage.[15] Due to the reports of its excellent processing performance, microwave–vacuum drying was employed in this study for the dehydration stage of new-paocai production.

The application of vacuum–microwave drying technology in the new-paocai industry has significant advantages, such as shortening the drying time, thus greatly reducing energy consumption; realizing the preservation and fermentation of paocai under lower salt concentration, effectively reducing the amount of salt used; maintaining the color, flavor and texture of paocai; and improving the sensory quality of the product. This technology not only improves production efficiency and reduces production costs, but also optimizes the product quality, which is in line with the modern consumers' demand for health and environmental protection. Therefore, vacuum–microwave drying technology is expected to become one of the key technologies for the future development of the pickle industry. The aim of this study was to determine the osmotic dehydration process conditions most suitable for the pretreatment of high quality new-paocai raw materials by investigating the influence of different rates of water loss resulting from microwave–vacuum drying in terms of the rehydration ratio, texture, vitamin C content, microstructure, color and sensory attributes.

2 Materials and methods

2.1 Microwave–vacuum drying process

Fresh radishes, uniform in shape and undamaged, were purchased from a local supermarket in Chengdu, China to be used as samples in this study. Surface soil was removed by washing the radish samples, which were then washed again, surface dried and cut into 3 mm thick fan slices. Next, fresh radish slices (200 g) were carefully and evenly distributed on a drying tray and placed in a microwave–vacuum drying oven (HWZ-2B, Tianshui Huayuan Pharmaceutical Equipment Technology Co., Ltd; Gansu, China) until their water loss rates were 30%, 35%, 40%, 45%, 50% and 55%, respectively. The dried samples were then packed into aluminum foil bags, vacuum-sealed using a vacuum packaging machine and stored at 4 °C for subsequent testing of the relevant indexes.

2.2 Rehydration ratio

Rehydration ratios were determined according to the method of Kahraman,[16] with some modifications. The dried radish slice samples (5 ± 0.50 g) were placed in 100 mL distilled water warmed to approximately 40 °C and left to soak for 40 min until the liquid was fully absorbed. Upon removal, they were gently blotted with filter paper to remove surface water before weighing. The assay was repeated three times for each group and the rehydration ratios were then calculated using eqn (1):

$$R_{\mathrm{f}} = \frac{D_2}{D_1} \tag{1}$$

where D_2 is the total weight after rehydration, and D_1 is the weight of the dried sample.

2.3 Vitamin C analysis

The determination of vitamin C content in radish slices with different water loss rates was performed with reference to Sun's method.[17] The samples were weighed (4.00 g) and placed in 50 mL brown centrifuge tubes, to which 20 mL of 2% acetic acid solution was added. They were then extracted using an ultrasonic water bath for 15 min, centrifuged at 4000 rpm for 3 min, and then transferred to a 50 mL volumetric flask, whereafter the supernatant was collected and transferred to the same volumetric flask twice. Sample extracts were obtained by bringing the volume to 50 mL with 2% acetic acid solution, and they were filtered through a 0.22 μm microporous organic membrane (nylon) prior to analysis. The ascorbic acid standard was purchased from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China), and the standard curve within the 0–100 μg mL^{-1} linear range was $Y = 41.449\ X = 8.8159$ ($R^2 = 0.9998$).

2.4 Determination of texture

The texture properties of radish samples subjected to different levels of drying were measured using a TA-XT PLUS texture analyzer (Stable Micro Systems, Surrey, UK) equipped with a P/36R probe, according to the method described by Antal,[18] but with minor modification. Additional parameters were set as follows: induction force, 5.0 g; compression distance, 1 mm; pre-test, test and post-test speed, 2.0 mm s^{-1}. The sample was placed on the test table and its pressure peak was determined (in terms of deformation, time, quality and composition) to record the hardness, chewiness, gumminess and springiness.

Nine triplicate experiments were performed for each sample, and the results were averaged.

2.5 Microstructure measurement

To meet the requirements of scanning electron microscope (SEM) processing, the radish samples were pre-treated according to the method of Wang.[19] First, the samples were pre-cooled in an ultra-low temperature refrigerator for 12 h, and then dried for 36 h in a vacuum freeze-drying machine. SEM analysis was performed based on the method of Bao,[20] with some modifications. For measurement, the pre-treated samples (3.0 mm × 3.0 mm) were fixed on the SEM support and then coated with gold–palladium in an ion sputter coater under vacuum for 3–4 min. After processing, the samples were observed with SEM in high-vacuum mode at an accelerating voltage of 3.0 kV, and then examined at magnifications of 50×, 100× and 300× to identify surface characteristics.

2.6 Color assessment

Color assessments were carried out according to the method described by Xu,[21] using the VeriVide DigiEye digital electronic eye (Nikon Corporation, Japan). The instrument was preheated and calibrated before the shutter speed and aperture size were adjusted to RGB values ranging from 215 to 225. The radish samples were distributed evenly on the white sample plate and placed in the closed light box, and the 'Camera-Photo' window was then activated to obtain the required images, from which the L^*, a^* and b^* values were determined. The colors of the variously dried radish slices were randomly recorded, and color differences (ΔE) were calculated using the following formula:

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

where ΔE is the difference between the colors of fresh radish and dried radish; L^*, a^* and b^* are the color parameters of the sampled dried radish, and L_0, a_0 and b_0 represent the color parameters of the fresh radish.

2.7 Sensory evaluation analyses

A sensory panel of 16 extensively trained evaluators (8 men and 8 women) was invited to evaluate sensorial properties such as color, smell, shape, texture, and total points, and sensory analysis was carried out by using the Hedonic Scale (rating 1–9).

2.8 Data analysis

All experiments were performed in triplicate and the results are expressed as mean ± standard deviation (SD). The data statistics and graphs were acquired using Excel 2010, SPSS 20.0 and Origin 2022 software. $P > 0.05$ indicates an insignificant difference, while $P < 0.05$ indicates that the difference was significant.

3 Results and discussion

3.1 Effects of different drying parameters on the radish rehydration rate

Rehydration refers to the recovery process in dried products after water absorption. It was found that the different rates of water loss affected the rehydration performance of the radish samples, as shown in the rehydration rates in Fig. 1, and it was evident that the rate of rehydration increased in correlation with an increased rate of water loss. At water loss rates of 30% and 35%, the results showed that there was no significant difference between the radish slices ($P > 0.05$), However, their rehydration rates were significantly lower than those of the other treatment groups ($P < 0.05$), at 1.43% and 1.5%, respectively. When the radish water loss rate was 55% after the microwave–vacuum drying treatment, the sample rehydration rate was significantly higher than that of the other treatment groups ($P < 0.05$), reaching 1.96%; this means that the weight of the rehydrated radish sample was 1.96 times the weight of the dried sample, representing a 96% increase in weight during the rehydration process. A moisture content decrease from 70% to 65% resulted in the most significant increase in rehydration rate, reaching 0.16; however, when the moisture content decreased from 55% to 50%, the increase in rehydration rate was insignificant at just 0.03.

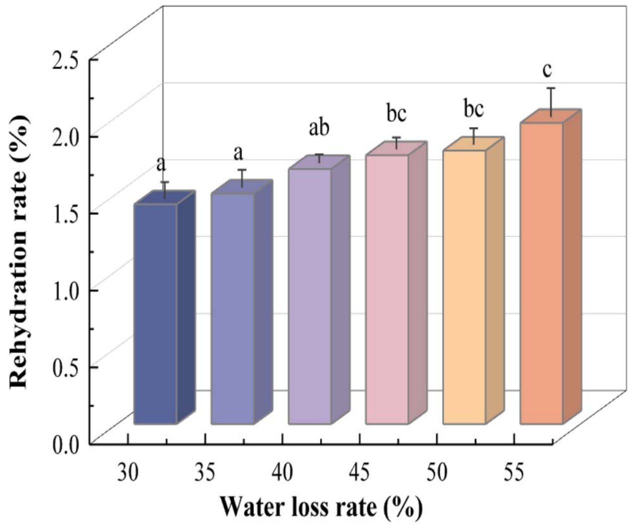

Fig. 1 Effects of different water loss rates on the rehydration rate of radish slices. There are significant differences between groups represented by different letters on the bar chart ($P < 0.05$).

Rehydration aims to restore the moisture properties of fresh fruit by bringing the dried product into contact with a rehydration solution.[22] During this process, the transfer of water from the solution to the internal cellular structures of the sample, and the movement of soluble solids from the fruit to the solution can take a long time. Furthermore, these processes can be influenced by varying pretreatments, drying methods, and drying and rehydration conditions.[23] In this study, the increase in microwave–vacuum drying time increased the evaporation rate of water and formed large vapor pressure in a short time, which enhanced the tissue expansion of radish slices and gradually improved their rehydration.[24] In the study of squid shreds, the rehydration rate of vacuum–microwave drying was significantly higher than that of hot air drying and solar drying.[25] In addition, rates of rehydration are affected by the structural integrity of samples. Rehydration can greatly improve the texture deterioration and structural damage caused by drying, thereby increasing the quality of dried radish slices; however, the loss of nutrients due to drying did not change significantly as a result of rehydration, and an increase in volume and quality was found to result in a corresponding decrease in the amount of nutrients per unit volume and mass.

3.2 Effects of different drying parameters on radish texture

Hardness, chewiness, gumminess and springiness were selected as evaluation indexes in the texture profile analysis, based on the characteristics of new-paocai texture and radish. Fig. 2 shows that the textural parameters varied in the radish slices with different rates of water loss. Increasing water loss resulted in a significant decrease in the hardness values of the samples, with the lowest decrease being 56.85% decrease while the highest was 97.15%. Compared with the untreated radish (11 927.22 g), the hardness of radish slices with a 30% water loss rate decreased to 5146.03 g, while at the maximum water loss rate of 55% the hardness of the radish slices was just 339.75 g. The chewiness and gumminess values of the dried samples were similar to those of their hardness, decreasing significantly with the increase in the water loss rate and reaching their lowest values at 238.84 g and 263.53 g, respectively. Conversely, the springiness of the radish slices was different from the other indexes. With the increasing water loss rate, the elasticity of the dried radish slices increased gradually, reaching a maximum value of 0.91 g. When the water loss rate exceeded 45%, the springiness value of the radish samples rose above that of the untreated samples, which was 0.85 g.

Most previous studies have shown that drying treatment exerts a considerable effect on the texture of fruits and vegetables. On the one hand, hardness is considered to be related to the force required to chew during consumption; it depends on the distance from skin to flesh, and hardness values are higher in the outer regions of the sample, closer to the skin. This phenomenon is related to the composition of the biological material that constitutes the skin, and particularly the cell-wall polysaccharides, which provide higher mechanical resistance.[26] On the other hand, drying treatment removes part of the water present in and between the cells of fruit and vegetable samples, reducing the filling and support of plant structures such as the cell wall, which leads to the disruption of cells and other structural tissues and results in the reduction of hardness. Hence, the effect of a particular drying method on hardness is highly significant for maintaining produce quality. Some studies have indicated that microwave–vacuum drying treatment significantly reduced the hardness of longan fruit, corncob and blueberry fruits compared to other high-temperature drying methods.[12,27,28] Springiness is a measure of recovery after compression caused by mastication and the speed of return to the original state after the removal of the deforming force. In a study of dried pears reported by Guiné *et al.*,[29] the water content of the fruit continuously reduced during the drying process accompanied by a simultaneous increase in sugar concentration, which caused the pears to soften. This concurs with the results of this work, in which the springiness value of the dried radish slices increased significantly with the decrease in moisture. Similarly, Kotwaliwale *et al.*[30] reported that as the degree of dryness increased in mushrooms, their springiness gradually increased. Furthermore, the drying process significantly reduced the chewiness of the radish slices in this study, once again due to the substantial reduction in their hardness.

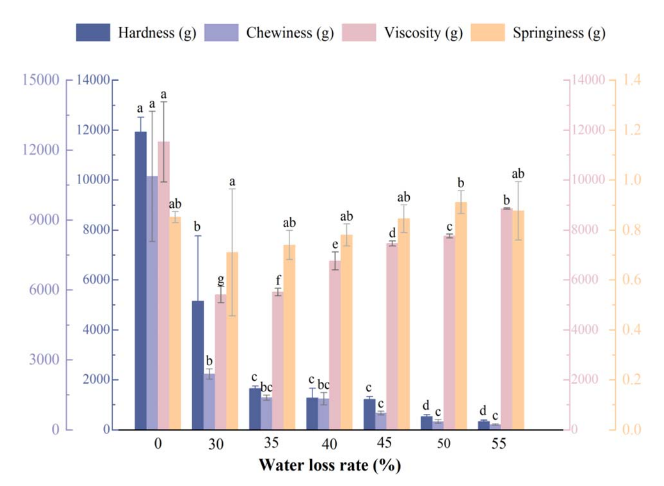

Fig. 2 Effects of different water loss rates on the texture of radish slices. Values with different letters (a–f) in color columns represent that they are significantly different from each other ($P < 0.05$).

3.3 Effects of different drying parameters on vitamin C content

Retention of vitamin C content is an important indicator for evaluating different processing and storage methods for fruits and vegetables, and dry weight-based vitamin C content more accurately reflects the effect of drying treatments on nutrient retention. Fig. 3 shows the changes in vitamin C content in radish with different water loss rates after microwave–vacuum drying. The results showed that the vitamin C content in fresh radish slices was as high as 61.51 μg g^{-1}; however, the vitamin C content in the treated groups of radish slices decreased significantly with rising rates of water loss ($P < 0.05$). Compared with the untreated samples, when the water loss rate of the drying samples was 55%, their vitamin C loss rate reached 84.02%, leaving a content of just 9.83 μg g^{-1}. The highest loss of vitamin C content, a decrease from 50.51 μg g^{-1} to 36.26 μg g^{-1}, was observed when the water loss rate increased from 30% to 35%. This phenomenon may be related to the water distribution in the cells. Compared with other groups, the loss of vitamin C content was the smallest, at just 5.29 μg g^{-1}, when the water loss rate rose from 40% to 45% in the dried radish slices.

Vitamin C is an unstable and water-soluble compound that is easily degraded at high temperatures and in the presence of excessive levels of oxygen, light and enzymes.[31] A study conducted by Gamboa-Santos *et al.*[32] showed that two most important factors in vitamin C loss in processed fruit and vegetables are temperature and drying time.[33] Demiray *et al.*[34] proved that vitamin C is susceptible to oxidation in the presence

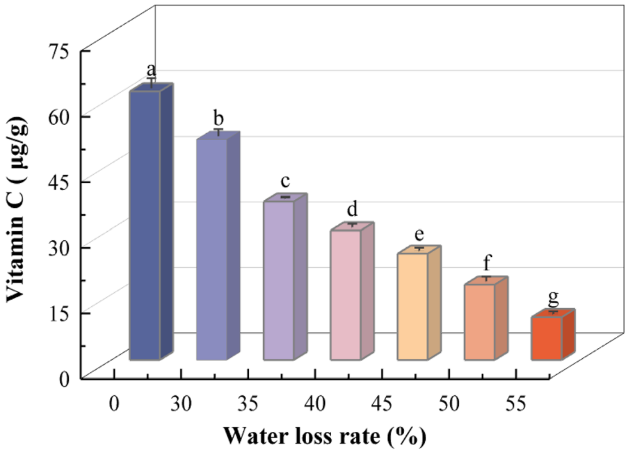

Fig. 3 Effects of the water loss rate on vitamin C content in radish slices. There are significant differences between groups represented by different letters on the bar chart ($P < 0.05$).

of high temperature and that its degradation rate increases incrementally with increasing drying temperature. Compared to other drying methods, the ability of a microwave field to generate heat throughout a food matrix can decrease its drying time by up to 90%, thus effectively reducing the loss of vitamin C.[35,36] Vacuum microwave drying treatment retains more bioactive compounds such as vitamin C, total flavonoids and total phenols in jujube powder compared to hot air drying treatment.[37] Another important factor influencing vitamin C degradation is the parameter of water activity. At high levels of activity, water content can dilute vitamin C concentration, inducing a low rate of degradation.[38,39] In this study, water loss in the drying radish was found to decrease its protective ability, subsequently accelerating the degradation of vitamin C, concurring with the abovementioned analyses.

3.4 Effects of different drying parameters on the radish microstructure

The microstructures of produce can provide direct evidence of the effects of drying treatment on the surface of samples. In this study, the effects of different water loss rates on the microstructure of new-paocai raw materials were studied *via* SEM, the results of which confirmed that the microstructures of the radish samples were significantly affected. As shown in Fig. 4 (CK1 and CK2), the gullies and texture on the surface of the control samples were clear, with an easily recognizable network of organizational structures. In contrast, with the increase in water loss rate, the three-dimensional structure of the surface of the radish slices gradually flattened, blurring the grain and making the network difficult to discern. When the water loss rate exceeded 50%, severe cell deformation, weakened uniformity and dislodged cell contents due to tissue swelling could be clearly observed, as shown in Fig. 4 (E and F). Moreover, obvious honeycomb pore structures appeared, creating large pores in the surface material of the radish slices, as observed at 100× magnification of the images, indicating an excessive loss of water. At a magnification of 400×, the gullies and three-

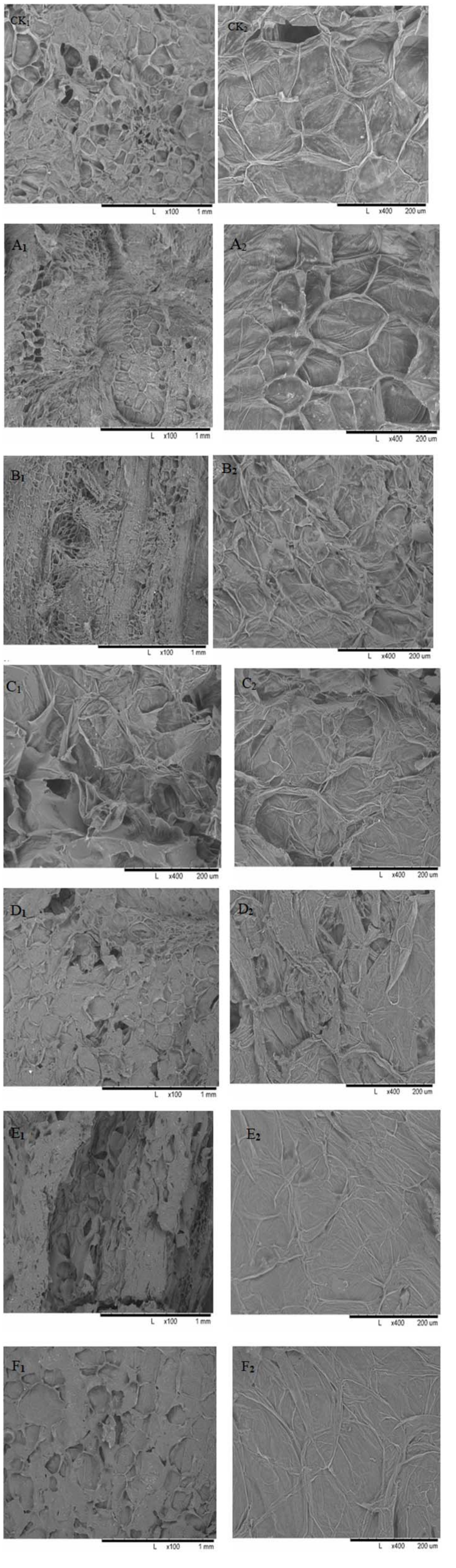

Fig. 4 Effects of different water loss rates on microstructure of radish slices. CK represents untreated (0%) and A, B, C, D, E, and F represent radish water loss rates of 30%, 35%, 40%, 45%, 55%, and 55%, respectively, with tail 1 for 100 and tail 2 for 400.

dimensional texture had clearly disappeared, leaving a flat network structure indicative of structural collapse. Considering the results of the above SEM observation, 45% was selected as the best water loss rate for drying radish.

Fresh radish is a high-moisture food comprising 93.40 ± 0.23% water, which is well retained. Principal stress is induced during the drying process, caused by changes in the moisture and temperature gradients, and these microstructural changes lead to the deformation of the radish. Zotarelli *et al.*[40] reported that drying leads to shrinkage and collapse in approximately half of the fruit structure due to microstructural stresses produced by large gradients in moisture in the material, which cause capillary collapse and irreversible structural changes. During drying, water content migrates from intracellular and intercellular spaces to the dry surface environment, causing the overall tissue deformation and volume reduction that is usually defined as material shrinkage.[41] Such shrinkage occurs for two reasons: first, because the tissue is unable to maintain its structural integrity when the areas previously occupied by water are continuously emptied and air-filled, causing the structure to become flat;[42] and, second, because the external skin structure collapses and shrinks.[43] In general, increased tissue dehydration and significant deformation of cell texture is associated with cell collapse due to the loss of cell turgor pressure during prolonged drying.[44] In terms of its spatial distribution, water in fresh tissues can be categorized into three types, namely intercellular water, intracellular water and cell wall water. Cell rigidity is mainly dependent on the distribution of water between cells, so intracellular water loss decreases turgor pressure, while intercellular water loss leads to the breakdown of cell-to-cell mutual support force.[41,45] Thus, the direct loss of water causes structural collapse in radish raw materials.

3.5 Effects of different drying parameters on radish color

Color is among the most significant sensory evaluation indicators for most foods, and undesired color changes are clear evidence of an adverse effect on their quality. As shown in Fig. 5, the radish samples underwent various color changes during the different drying treatments. The color of the control group was naturally white, with a clear pattern, a smooth surface and the best three-dimensional structure. Compared to the control group, the dried radish slices exhibited different degrees of yellowing and curling at the corners, and these changes became more obvious with the increase in the rates of water loss, particularly once the losses exceeded 45%. As shown in Table 1, ΔE reached its maximum value at a water loss rate of 55%, at 10.13 ± 0.78, which was significantly higher than that of the other groups ($P < 0.05$). Color lightness in the dried radish slices was measured and reported as the L^* value. The fresh samples were significantly brighter than the dried samples, indicating that the characteristic brightness of the radish slices gradually decreased with increasing water loss. The a^* values did not differ significantly ($P > 0.05$) between the treatment group with the lowest rate of water loss and the control group; however, substantial differences ($P < 0.05$) were observed in the groups where water loss exceeded 45%, probably due to the loss of water and external surface oxidation. The b^* value indicated increasing yellowness in the samples as the degree of dryness increased, rising from 0.18 to 8.60 as the water loss rate increased from 30% to 55%.

The Maillard reaction, to which the increase in a^* and b^* values of the treated radish slices was attributed, has been identified as the main non-enzymatic browning reaction that often occurs during the food drying process.[46] Liu *et al.*[47] found that the Maillard reaction caused the color of dried *Pleurotus eryngii* slices to darken with the increase in drying temperature. Drying fruits and vegetables at high temperatures over extended periods causes greater degradation of heat-sensitive bioactive compounds, such as carotenoids, and subsequently increases colour change in the dried products. Wang *et al.*[48] reported that the blanching of pepper resulted in a decrease in its L^* value, which was attributed to red pigment degradation and cell destruction. Color changes are also significantly linked to water loss, the collapse of cell structures and the degradation of nutrients.[49] Furthermore, studies have shown that shrinkage and structural deformation that occurs during drying may

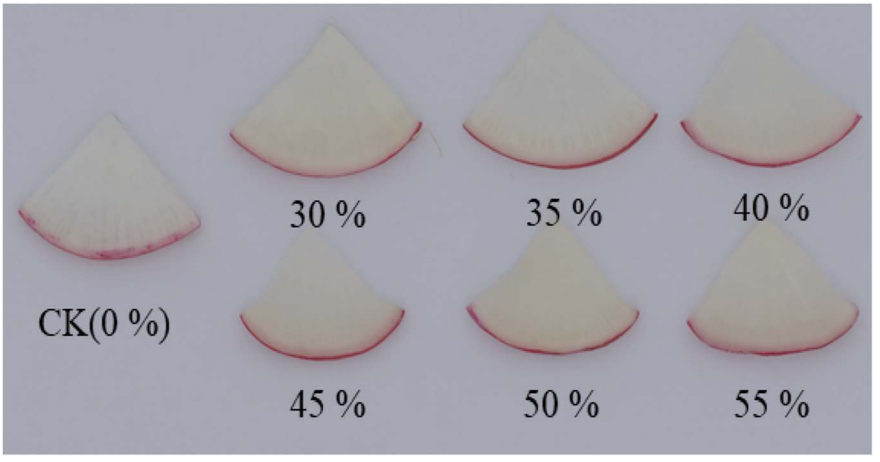

Fig. 5 Electronic eye measurement of radish slices with different water loss rates.

Table 1 Determination of color differences in radish slices with different water loss rates. Values are means ± SD. Values with different letters (a–f) in the same column are significantly different from each other ($P < 0.05$)

Water loss rates (%)	ΔE	L^*	a^*	b^*
CK	—	88.90 ± 1.92^{e}	1.44 ± 0.58^{a}	0.18 ± 0.30^{a}
30	2.80 ± 0.40^{a}	86.81 ± 0.70^{de}	1.59 ± 0.38^{a}	1.83 ± 0.46^{b}
35	2.66 ± 0.39^{a}	87.48 ± 0.41^{cd}	1.17 ± 0.25^{a}	2.38 ± 0.23^{c}
40	4.04 ± 1.88^{b}	85.69 ± 1.88^{bcd}	1.81 ± 1.12^{ab}	2.32 ± 0.24^{c}
45	4.69 ± 0.75^{b}	86.00 ± 0.53^{bc}	3.10 ± 1.36^{bc}	3.21 ± 0.28^{d}
50	7.52 ± 0.69^{c}	84.82 ± 0.67^{ab}	3.62 ± 1.46^{c}	5.90 ± 0.52^{e}
55	10.13 ± 0.78^{d}	83.60 ± 0.88^{a}	3.05 ± 0.83^{bc}	8.60 ± 0.41^{f}

result in the transfer of photons, absorption of brightness or a decrease in reflected and diffused light due to the reduction of moisture during drying, which may explain the drastically diminished luminosity in the radish slices, which reduced their L^* values.[50] The significant color changes observed in this study's microwave-vacuum dried radish slices were the same as those reported by Setiady,[51] and greater degrees of drying led to more pronounced changes in ΔE, a^* and b^*.

3.6 Effects of different drying parameters on sensory evaluation

The sensory evaluation results for the radish slices with different water loss rates after microwave–vacuum drying treatment are presented in Fig. 6, in which it can be seen that, with increasing rates of water loss, the sensory properties of all samples showed a downward trend. For example, the sensory score of the 30% water loss group was significantly higher than that of the other groups ($P < 0.05$), at 8.07, followed by the other samples at 7.88, 7.48, 7.26, 6.73 and 6.08. When the water loss rate was 35%, the sample color value was significantly higher than those of the other treatment groups ($P < 0.05$), reaching 7.79. Water loss can also significantly affect the smell of radishes and, as the rate of water loss increased in the samples, their smell score gradually decreased, with the lowest smell score reaching just 5.77. Smell, shape and texture scores were not significantly different ($P > 0.05$) in the water loss rate groups of 40% and 45%; however, in the groups where water loss exceeded 45%, a sharp decrease in sensory scores was evident. This phenomenon may be attributed to the excessive dehydration caused by microwaving the radish slices, which substantially affected their microstructure, causing significant structural collapse and texture softening. Color changes and shape wrinkles were also obvious in the groups with water loss rates between 30% and 45% compared to the control samples, which would affect consumer evaluation of the quality of radish paocai. The above comprehensive evaluation indicated that the group treated with a water loss rate of 45% was optimal for consumer demand.

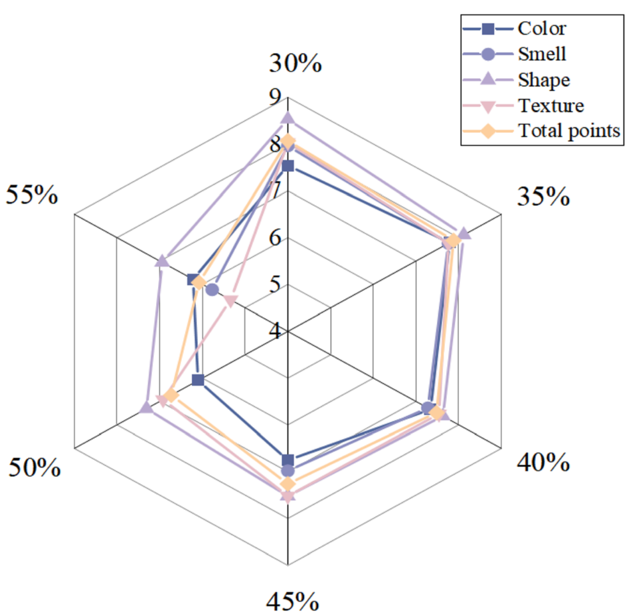

Fig. 6 Sensory evaluation results of radish tablets with different water loss rates.

Sensory evaluation is a vital index for the quality of post-harvest fruits and vegetables. In this study, the sensory score of the microwave–vacuum dried groups were significantly influenced by the microwave dehydration of the radish slices, which substantially destroyed their texture, making recovery difficult. The microwave–vacuum drying treatment, performed in a light-proof, low-oxygen environment, averted color damage to a certain extent, and was consistent with the findings of Bai *et al.*[52] when treating *P. eryngii* with different drying methods. However, the higher rate of water loss deepened the color, resulting in a lower color score, possibly due to surface oxidation of the radish. Microwave–vacuum drying, as well as longer drying times, can cause greater degradation of heat-sensitive bioactive compounds, such as carotenoids, which would have subsequently intensified the colour changes in the radish samples. In combination with hot drying, microwave–vacuum drying has the effect of removing smells from the material, in this study reducing the fragrance of the treated groups of radish. High temperature also caused certain biochemical reactions that affected the smell of the radish slices, resulting in a decreased radish smell score with increasing rates of water loss. Changes in shape and texture are similar to those in color, smell and the total score, mainly due to cell collapse and texture softening caused by dehydration. The lower the water content of radish, the more serious its tissue collapse and cell wall damage.

4 Conclusion

The results of this study clearly demonstrated the significant effects exerted by the drying process on the nutrients, appearance and texture of raw radish slices for the production of paocai. The measurements showed that the rehydration rate and ΔE increased during microwave–vacuum drying, while the vitamin C content and hardness significantly decreased with the gradually increasing rate of water loss compared to the fresh, untreated radish slices. However, when the water loss rate exceeded 45%, the radish samples exhibited pronounced structural collapse, resulting in lower sensory scores than those of the lower water loss groups. After comprehensive evaluation, the radish group with a water loss rate of 45% was selected as the most suitable for subsequent paocai production, as its overall performance was better than those of the other test groups and it facilitated the recovery of various original qualities during penetration. In conclusion, this study not only provides a theoretical basis for selecting optimal pretreatment conditions in new-paocai production, but also carries direct industrial implications. The application of vacuum microwave drying can significantly reduce energy consumption by shortening drying time and decrease the reliance on high-salt storage methods; it also aligns with growing consumer preferences for healthier, lower-sodium fermented foods. These findings can serve as a guide for improving production efficiency and sustainability in the pickle industry.

Data availability

All data generated or analyzed during this study are included in this published article.

Conflicts of interest

No conflicts of interest to declare.

Acknowledgements

This work was supported by the Science and Technology Program (Regional Innovation Co-operation Project) of Sichuan province (2024YFHZ0207), the Key project of technological innovation and application development special item in Chongqing (cstc2021jscx-cy1hX0014) and the Open Research Subject of International Science and Technology Cooperation (Australia and New Zealand) Institute of Sichuan (AXYJ2022-012 and AXYJ2022-013).

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