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Research article

Microwave heating concentration of raspberry pulp: Evaluation of processing variables on concentration characteristics and quality attributes

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ABSTRACT

Concentration of fruit pulp is an important unit operation in food processing and has a wide range of applications. In this study, the microwave heating concentration (MHC) of raspberry pulp at different microwave powers, heating times and sample masses were investigated considering concentration characteristics and quality attributes. The results showed that increasing microwave power/heating time or decreasing sample mass significantly decreased the moisture content but had no significant effect on the temperature of raspberry pulp, while these conditions resulted in loss of total anthocyanin content and deterioration of total color difference. LF-NMR and SEM results revealed that the changes in temperature and moisture content caused by MHC significantly affected the total anthocyanin content and total color difference of the final product. Microwave power of 800 W, heating time of 3 min and sample mass of 90 g are selected as suitable parameters for MHC of raspberry pulp. This study may provide guidance for the development of appropriate technology for MHC of berry pulp.

1. Introduction

Raspberries (*Rubus idaeus* L.) are rich in a variety of bioactive compounds such as anthocyanins, vitamin C, antioxidants and phenolic substances [1]. However, fresh raspberries are highly perishable due to their fragile structures and high moisture content of over 80 % (*w.b.*), resulting in quality deterioration and short shelf life [2]. The development of novel raspberry products such as fruit powders and concentrated juices or pulps is a potential way to extend shelf life and increase economic value compared to the sale of fresh harvested raspberries [3]. Heating or drying treatments are necessary processing steps to produce above mentioned novel raspberry products by reducing the moisture content to the desired level [4]. However, producing fruit powders and concentrated pulps or juices from raw raspberry pulp requires long drying times and high energy consumption using conventional drying methods such as hot air drying, ohmic heating, freeze drying and spray drying [4,5] and microwave-assisted freeze drying [6–8]. Therefore, it will be an available method to remove the most of the water from the material using concentration technology prior to conventional drying, which can reduce drying time and energy consumption to ensure high product quality. Concentrated fruit pulp or juice not only reduce storage and transportation costs, but also are frequently used as important additives in the processing of fruit-based snacks such

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Abbreviations

MHC	Microwave heating concentration
MC	Moisture content
LF-NMR	Low field nuclear magnetic resonance
SEM	Scanning electron microscope

as raspberry chips [9].

Food concentration technology is based on physical separation methods to remove a certain amount of water from liquid foods. Conventional concentration methods mainly include vacuum concentration [10], freeze concentration [11], membrane permeation concentration [12]. Vacuum concentration technology from the low boiling point of water in a vacuum environment may achieve liquid concentration at a relatively low temperature [10]. Freeze concentration technology achieves liquid concentration by freezing some of the water in the liquid and converting into precipitated ice crystals to remove water [11]. Although vacuum and freeze concentration technologies have low nutrient losses, they have low efficiency and high costs compared to thermal concentration methods. In addition, membrane permeation concentration comes from the pressure and concentration difference on both sides of the polymer film as the driving force for the separation, purification and enrichment operations to purify each component in the liquid sample to achieve the concentration objectives [10]. This technology has significantly improved the quality of the concentrated product, but has high membrane costs and low throughput capacity. Recently, microwave heating concentration (MHC) technology [13,14], based on the thermal effect generated by the absorption of microwave energy by dielectric materials in the microwave field, is introduced to concentrate fruit pulp or juice [13]. Compared to frequently-used concentration technologies, MHC has the advantages in lower cost and higher efficiency [13]. In addition, the similarity between MHC and microwave drying is that both are based on the principle of microwave heating to achieve dehydration. The difference lies in the final moisture content of the material. Microwave drying requires most of the water to be removed to meet food storage requirements, whereas MHC only removes some water from the sample and the residual moisture content in the sample is generally higher than that treated with microwave drying.

The MHC process and the changes in product quality after concentration have been widely studied. Maskan [15] investigated the feasibility of MHC of pomegranate juice and found that MHC had a lower degree of color loss compared to rotary vacuum concentration. Fazaeli et al. [16] studied the quality changes of black mulberry juice after conventional concentration and MHC under different operating pressures, and the retention of anthocyanins and the color in the concentrated product was better under MHC. Elik et al. [17] studied the quality differences of concentrated blueberry juice under different concentration processes and found that MHC has a higher efficiency than rotary evaporation concentration, but excessive microwave intensity has a negative effect on the color and phenolic substances of the concentrated product. Therefore, an understanding of the MHC process, in particular the concentration characteristics and quality attributes, is critical to the reasonable control of MHC technology, which provide the basis for improving concentration efficiency and final product quality.

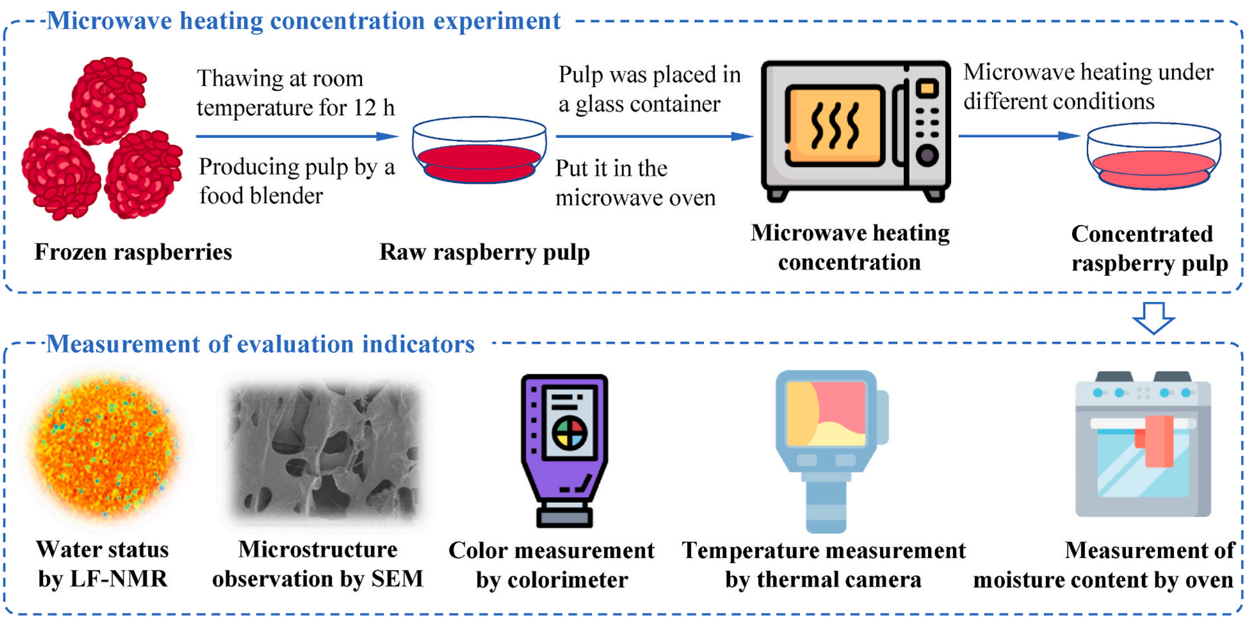

Fig. 1. Experimental procedures of MHC of raw raspberry pulp. Note: MHC, Microwave heating concentration; LF-NMR, Low field nuclear magnetic resonance; SEM, Scanning electron microscope.

To our knowledge, existing researches mostly focus on the concentration of fruit juices such as orange juice [18], apple juice [19,20], grape juice [21,22], etc. However, little research has been done on the MHC of berry pulps, such as raspberry pulp, which is a typical food material with high viscosity, heat sensitivity and high water-holding capacity than other fruit juices [23]. Knowing about the concentration properties of liquid foods can enhance the understanding of the concentration process and quality changes, and also leads to the development of appropriate concentration technology to achieve the desired product quality [24]. Therefore, the present study aims to evaluate the concentration characteristics and quality attributes of raspberry pulp under MHC at different processing variables including microwave power, heating time and sample mass. The contributions of the current work are expected to improve the understanding of MHC of raspberry pulp and provide the basis for future process optimization and quality control, e.g. laying the foundation for a temperature-controlled MHC strategy of raspberry pulp to achieve higher quality.

2. Materials and methods

2.1. Sample preparation

Frozen raspberries were purchased from Gaotai Food Co., Ltd. (Harbin, China), thawed overnight (approximately 12 h) at room temperature (23 ± 2 °C), and then homogenized into pulp using a food blender. To simplify the description in the following text, the frozen-thawed raspberry pulp in this study was referred to as raw raspberry pulp and its initial moisture content was determined as 86.25 ± 0.87 % (*w.b.*).

2.2. Microwave heating concentration

Fig. 1 shows the experimental procedures of microwave heating concentration (MHC) of raw raspberry pulp. The MHC experiments were performed in a microwave oven without a turntable (*N*N-DS900, Panasonic, Osaka, Japan) at an operating frequency of 2450 ± 50 MHz. The microwave oven is designed using variable frequency technology, which allows the magnetrons to continuously and accurately adjust the microwave output power, providing continuous microwave output power and heating. The microwave oven used is factory preset with five different microwave power levels (100, 300, 440, 600, 800 and 1000 W) and can achieve continuous heating at each microwave power level during the microwave heating process.

In this study, 600, 800, and 1000 W were selected as different levels of microwave power as one of the experimental variables. The other experimental factors were determined as sample mass (70, 80, 90, 100 and 110 g) and heating time (2.0, 2.5, 3.0, 3.5 and 4.0 min). In this study, a target concentrated moisture content for MHC of raw raspberry pulp is around 76 % (*w.b.*). The experimental details were briefly described as follows. The raw raspberry pulp was placed on a glass tray, and then the tray was placed in the microwave cavity to be subjected to microwave heating until the target moisture content was reached. The tray had no lid to avoid splashing, as no obvious splashing was observed on the surface of the sample. Finally, the evaluation indicators including moisture content, temperature, color, microstructural changes and water status in the sample were measured. Each test for each treatment was performed in triplicate.

2.3. Measurement of temperature and moisture content

The measurement of temperature was referred to the method described by Zhang et al. [25]. Once the MHC experiment was completed, the sample was quickly taken from the microwave cavity and immediately infrared thermal imaging was performed using an infrared thermal camera (FLIR E95, FLIR Systems Inc., USA) to measure the temperature distribution. The obtained thermal images were then used to calculate the overall temperature of the sample using FLIR Tools software. It should be noted that, due to the thin thickness of the sample and the difficulty in directly measuring the temperature of the inner zones, the temperature collected from the infrared thermal images was regard as the temperature evaluation indicator.

For the determination of moisture content (*MC*), it was referred to the method of Yuan et al. [26] according to the oven method with 105 °C, and *MC* was calculated as Eq. (1):

$$MC = \frac{W_1\text{-}W_2}{W_1} \tag{1}$$

where *MC* is the moisture content (g/g); W_1 is the initial weight of the sample (g); W_2 is the final weight of the sample (g).

2.4. Determination of total anthocyanidin content

The total anthocyanidin content of raspberry pulp was determined by using the pH-differential method, and specific details were provided in previous work [27]. The absorbance of the sample at 525 nm and 700 nm was measured using a spectrophotometer (I9, Haineng Inc., Ltd., Jinan, China), and deionized water was selected as the reference. The total anthocyanidin content was calculated as cyanidin-3-glucoside equivalent by using Eqs. (2) and (3) [27]:

$$A = (A_{525\text{nm}}\text{-}A_{700\text{nm}})_{pH1.0} - (A_{525\text{nm}}\text{-}A_{700\text{nm}})_{pH4.5} \tag{2}$$

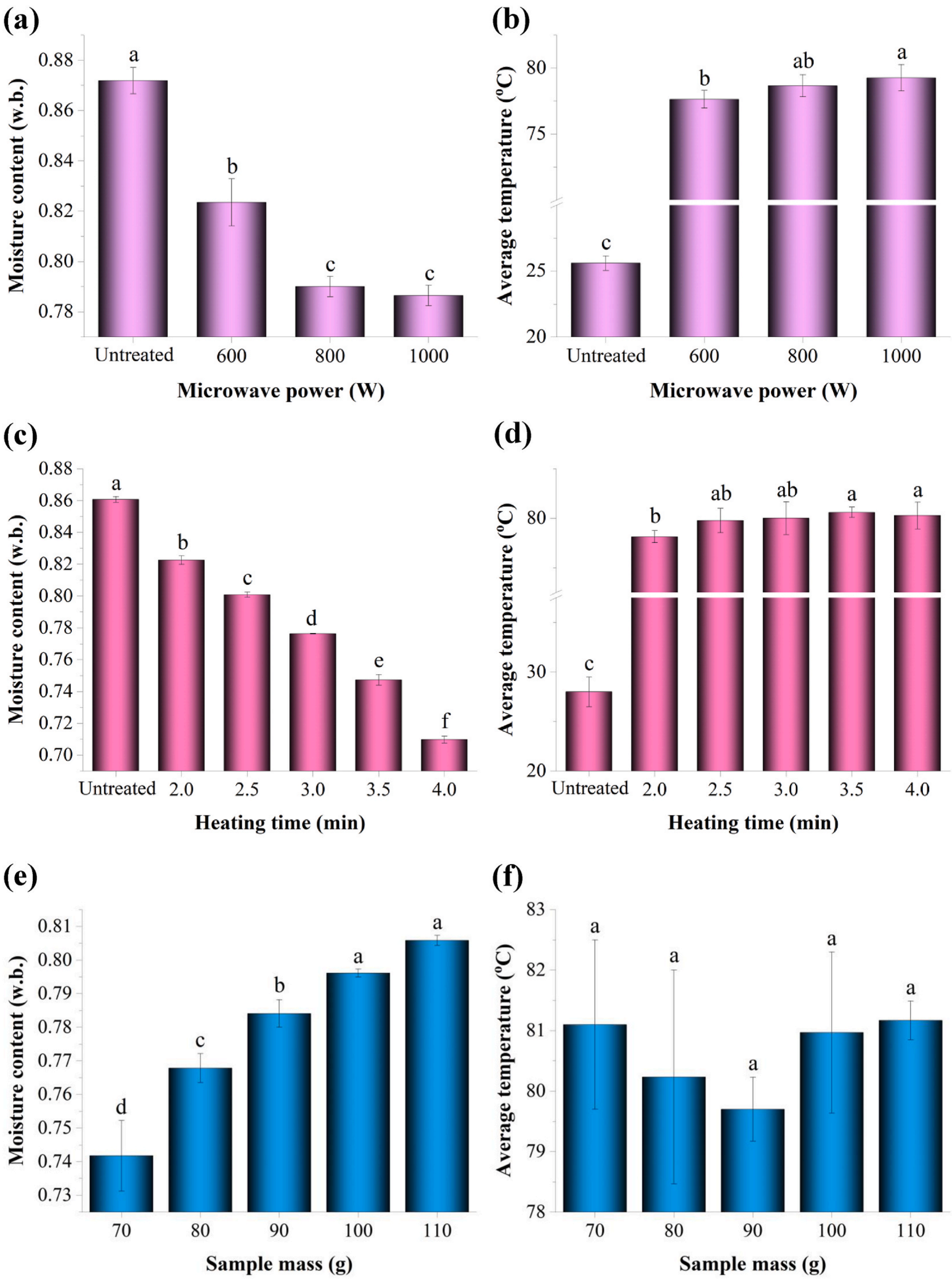

Fig. 2. Effects of different processing variables (microwave power, heating time, and sample mass) on the concentration characteristics (moisture content and average temperature) of raspberry pulp.

(a, b) Effects of the microwave power from 600 to 1000 W on the concentration characteristics of raspberry pulp at a fixed heating time of 3 min and sample mass of 90 g;

(c, d) Effects of the heating time from 2 to 4 min on the concentration characteristics of raspberry pulp at a fixed microwave power of 800 W and sample mass of 90 g;

(e, f) Effects of the sample mass from 70 to 110 g on the concentration characteristics of raspberry pulp at a fixed microwave power of 800 W and heating time of 3 min.

$$C = \frac{A \cdot Mw \cdot V \cdot DF}{\varepsilon \cdot L \cdot m_{db}} \quad (3)$$

where A is the absorbance; Mw is the molecular weight of cyanidin-3-glucoside (449.2 g/mol); DF is the dilution factor; V is the volume of the extract (mL); C is the content of cyanidin-3-glucoside (mg/g); ε is the molar extinction coefficient (26,900) of cyanindin-3-glucoside; L is the cell path length (1 cm); m_{db} is the mass of the dry matter (g).

2.5. Measurement of color value

The color values of the sample were measured using a colorimeter (CR-20, Konica Minolta, Inc., Japan) according to the method described by Gao et al. [28]. L^*, a^*, and b^* represent the brightness/dullness in a range of 0–100, redness (+)/greenness (−), and yellowness (+)/blueness (−), respectively. The total color differential (ΔE^*) was calculated from the measured color values using Eq. (4) [28]:

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

where L_0^*, a_0^* and b_0^* are the color values of the raw raspberry pulp; L^*, a^*, and b^* are the color values of raspberry pulp after specified treatments.

2.6. Low field nuclear magnetic resonance (LF-NMR)

The LF-NMR test was used to investigate the water status using an LF-NMR analyzer (Niumag Co., Ltd., Suzhou, China) based on the method described by Liu et al. [29] with some modifications. Briefly, the main setting parameters are as follows: proton resonance frequency, sampling frequency, time echo, number of echoes and scans were 21 MHz, 200 kHz, 0.4 ms, 12000 and 4, respectively. In addition, the data collected was also used to obtain the transverse relaxation (T_2) curve and to perform imaging to generate the MRI images through the analysis software equipped with the LF-NMR analyzer.

2.7. Scanning electron microscope (SEM)

The microstructure of the sample was observed by SEM (S-3400 N, Hitachi, Ltd., Tokyo, Japan) referred to the method of Liu et al. [30] with appropriate modifications. In brief, the samples were first freeze-dried, then cut into 1–2 mm slices, mounted on aluminum stubs using double-sided tape, sputter-coated with a thin layer of gold and finally observed the microstructure at 500 × magnification.

2.8. Statistical analysis

All experiments with different treatments were repeated in triplicate and experimental data were expressed as mean ± standard deviation. Significant differences between different treatments were evaluated by analysis of variance (ANOVA) with Tukey's test ($P < 0.05$) using SPSS software (Ver. 26.0, SPSS Inc., Chicago, IL, USA). The data plotting was performed by using Origin software (Ver. 2022, Origin Lab Corporation, Northampton, USA).

3. Results and discussion

3.1. Analysis of concentration characteristics of raspberry pulp under MHC

The concentration characteristics of raspberry pulp under microwave heating were evaluated by the changes in moisture content and average temperature under different processing variables, including microwave power, heating time and sample mass, as shown in Fig. 2.

3.1.1. Effects of microwave power on the concentration characteristics of raspberry pulp

Fig. 2a and b show the effects of microwave power in the range of 600–1000 W on the moisture content and average temperature of raspberry pulp at a fixed sample mass of 90 g and heating time of 3 min. Overall, increasing microwave power showed a significant ($P < 0.05$) decrease in moisture content (shown in Fig. 2a) and increase in average temperature (shown in Fig. 2b) under the fixed sample mass of 90 g and heating time of 3 min. This result was attributed to the fact that high microwave power promotes more absorption of microwave energy and the generation of volumetric heat in dielectric material such as raspberry pulp, resulting in a rapid temperature rising to remove water inside material [28]. However, the changes in moisture content and average temperature were found to be insignificant ($P > 0.05$) for 800 and 1000 W, which could be attributed to the small temperature difference due to the short heating time [28], resulting in statistical insignificance. This implied that the microwave power of 800 W is suitable for MHC of raspberry pulp, which can obviously improve the temperature and reduce the moisture content to the target one.

3.1.2. Effects of heating time on the concentration characteristics of raspberry pulp

Fig. 2c and d show the changes in moisture content and average temperature of raspberry pulp at heating times of 2–4 min for a

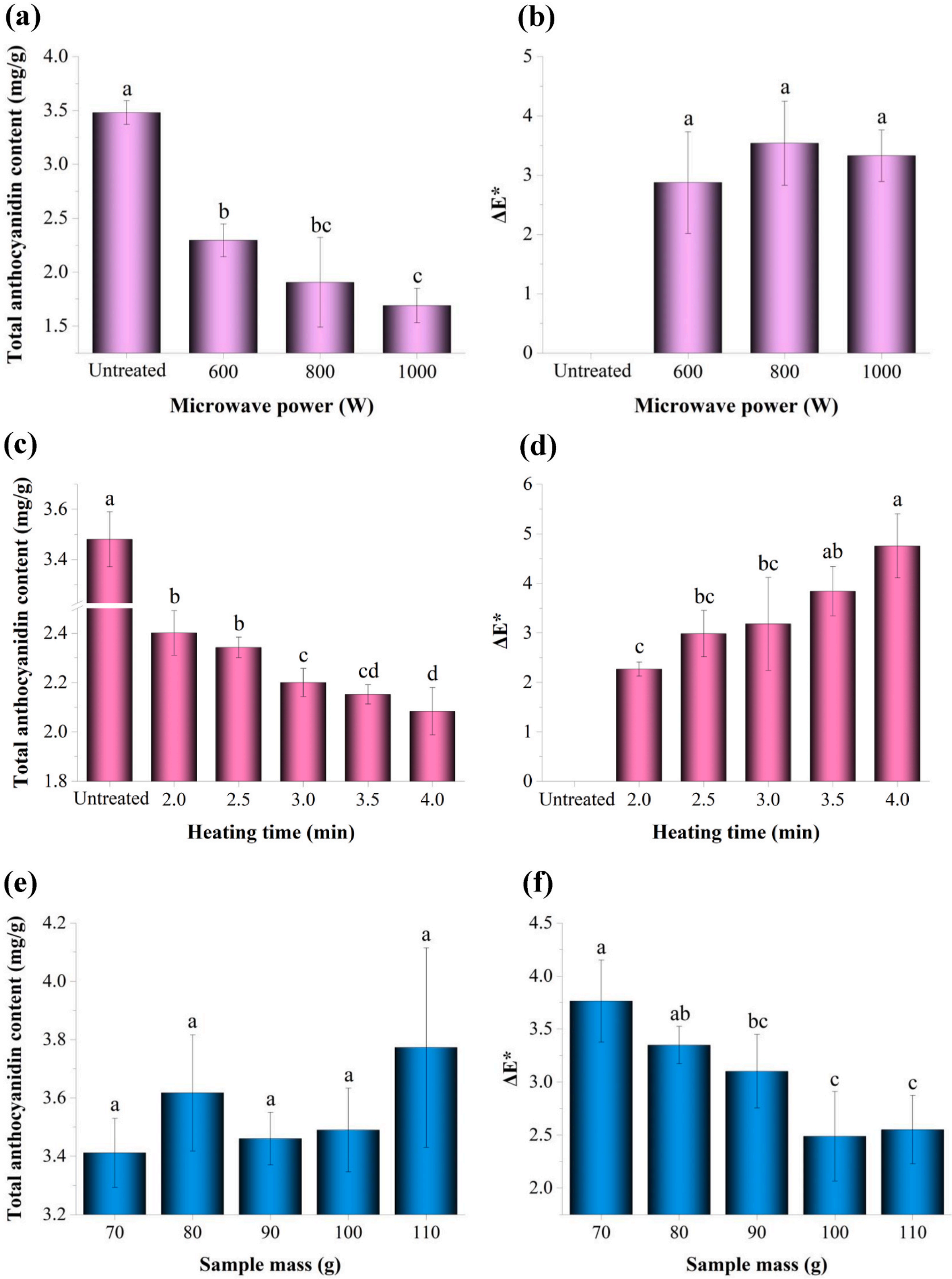

Fig. 3. Effects of different processing variables (microwave power, heating time, and sample mass) on the quality attributes (total anthocyanin content and total color changes) of raspberry pulp.
(a, b) Effects of the microwave power from 600 to 1000 W on the quality attributes of raspberry pulp at a fixed heating time of 3 min and sample mass of 90 g;
(c, d) Effects of the heating time from 2 to 4 min on the quality attributes of raspberry pulp at a fixed microwave power of 800 W and sample mass of 90 g;
(e, f) Effects of the sample mass from 70 to 110 g on the quality attributes of raspberry pulp at a fixed microwave power of 800 W and heating time of 3 min. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

fixed sample mass of 90 g and microwave power of 800 W. Compared with the untreated sample (raw raspberry pulp), the moisture content decreased significantly ($P < 0.05$) as the heating time progressed. This was because under heat treatment such as drying, the removal process of water from liquid to vapor is unidirectional and irreversible; when the thermal driving force changes to capillary pressure inside the material, the water continuously migrates from the inside to the outside of the material, and eventually reduces the water content of the material by surface convection [31]. As for the average temperature changes in Fig. 2d, it shows an initial rapid increase (0–2 min), followed by a gradual increase (2–3 min) and then a relatively stable level (3.5–4 min). The temperature changes of the sample depend on the heat accumulation inside material due to microwave energy absorbed by the material [32]. In the early stages of heating, due to the high moisture content, the microwave energy absorbed by the material will gradually increase its temperature. However, as the moisture content decreases, the microwave energy absorbed by the material will decrease, the temperature rise amplitude will slow down and the final temperature of the material will gradually tend to be relatively stable [33]. Overall, increasing heating time accelerates the water removal but improve the temperature to a limited extent for MHC of raspberry pulp. The heating time of 3 min is suitable for MHC of raspberry pulp.

3.1.3. Effects of sample mass on the concentration characteristics of raspberry pulp

Fig. 2e and f show the changes in moisture content and average temperature of raspberry pulp at sample mass of 70–110 g for a fixed heating time of 3 min and microwave power of 800 W. As the sample mass increases, the moisture content shows a significant increase, while the average temperature shows an insignificant change with a large fluctuation. This is because increasing sample mass means a reduction in the absorption of microwave energy per unit mass, thereby reducing the driving force of moisture removal [31]. However, the change in average temperature is mainly due to the significant effect of changes in sample mass on the uniformity of microwave heating. Due to the transmission of microwave standing waves, the variation in average temperature is significant, which in turn affects the temperature distribution of the final material [31]. In summary, the less sample mass had the quicker water removal to achieve the target moisture content. Considering the quality attributes of the final product, a relatively low temperature is favorable for maintaining heat sensitive components such as total anthocyanidin content, therefore the sample mass of 90 g may be suitable for MHC of raspberry pulp.

3.2. Analysis of quality attributes of raspberry pulp under microwave heating

The effects of different processing variables on the quality attributes of the final raspberry pulp, including total anthocyanidin content and color changes, were evaluated as shown in Fig. 3.

3.2.1. Effects of microwave power on the quality attributes of raspberry pulp

For the fixed sample mass of 90 g and heating time of 3 min, the effects of microwave power on total anthocyanin content and total color changes of raspberry pulp are illustrated in Fig. 3a and b, respectively. As shown in Fig. 3a, increasing microwave power significantly ($P < 0.05$) reduces the total anthocyanin content of the final raspberry pulp compared to the untreated sample (raw raspberry pulp). This is mainly attributed to the heat sensitivity of anthocyanin, as a typical component in berries, in thermal degradation caused by the gradual increase in temperature as microwave power increases [27]. A significant decrease in the anthocyanin content of hibiscus under microwave vacuum concentration was also reported by Dinçer et al. [34]. As shown in Fig. 3b, microwave treatment has significant effects ($P < 0.05$) on the total color difference (ΔE^*) of raspberry pulp compared with untreated one, while increasing microwave power shows insignificant influence ($P > 0.05$). This could be ascribed to small color loss due to relatively low sample temperature with increasing microwave power (in Fig. 2b). However, Dinçer et al. [34] noted that the microwave vacuum concentration did not cause a statistically significant change in the color values of the samples. This is different from our findings, and the differences between them may be caused by different sample temperatures under different processing conditions. Overall, 600 W is an appropriate level among the different microwave power levels.

3.2.2. Effects of heating time on the quality attributes of raspberry pulp

Under the fixed sample mass of 90 g and microwave power of 800 W, the effects of heating time ranging from 2 to 4 min on the total anthocyanin content and total color difference (ΔE^*) of raspberry pulp are shown in Fig. 3c and d, respectively. Compared with the untreated sample, the total anthocyanin content and ΔE^* of raspberry pulp decreased significantly ($P < 0.05$) with increasing heating time. This was because the absorption of microwave energy increased with heating time, resulting in a higher temperature (Fig. 2d) that reduced the total anthocyanin content through thermal degradation and exacerbated the color difference through Maillard reaction and pigment degradation [28]. It has been reported that during the concentration process, sugars and their degradation products accelerate the degradation of anthocyanins (pigments in raspberry pulp) and undergo non-enzymatic browning [15]. Xue et al. [27] also revealed a similar finding that the content of anthocyanins in blueberry puree decreased with temperature fluctuations and a decrease in water content. Therefore, a short heating time corresponding to low temperature conduces to obtain a high product quality only from the perspective of product attributes.

3.2.3. Effects of sample mass on the quality attributes of raspberry pulp

For the fixed heating time of 3 min and microwave power of 800 W, the effects of sample mass on total anthocyanin content and total color difference (ΔE^*) are shown in Fig. 3e and f, respectively. As displayed in Fig. 3e, increasing sample mass shows insignificant ($P > 0.05$) effects on total anthocyanin content with a large fluctuation but significant one for ΔE^* of raspberry pulp ($P < 0.05$). Although increasing sample mass means increasing the total anthocyanin content per unit mass, the insignificant changes in total anthocyanin content between different sample treatments result from the inhomogeneous changes of overall sample temperature due to uneven microwave heating [27], which was detailly explained in section 3.1.3. The total color difference (ΔE^*) indicates a significant decrease with increasing sample mass due to the high temperature for less sample mass leading to color difference caused by Maillard reaction and pigment degradation [31]. It has been reported that in microwave-assisted foam drying of blueberry pulp, the temperature above 75 °C resulted in a decrease in total anthocyanin content, and excessive temperature also caused the browning appearance of the product related to pigment decomposition and Maillard reaction [28].

3.3. Revealing the relationship between concentration characteristics and quality attributes

For microwave-concentrated raspberry pulp, the higher the total anthocyanin content in the raspberry pulp after MHC, the better the processing quality due to the lower nutritional loss. However, the lower total color difference (ΔE^*) means the less color loss and the more original color appearance of the product preserved [28]. According to Fig. 3b, d and 3f, the processing conditions for the smaller ΔE^* are low microwave power of 600 W, short heating time of 2 min and high sample mass of 110 g. This is also in line with common sense as the temperature of the material is relatively low under the above conditions, resulting in the lowest color loss of the product. Fig. 4 shows the changes in the actual color appearance of the product under different processing variables, where the color changes during MHC can be visually observed. From the perspective of data statistics, integrating the adequacy of 800 W to achieve the target moisture content (around 76 %) in Fig. 2a and the insignificant changes in total anthocyanin content between 600 and 800 W in Fig. 3a, the microwave power of 800 W was chosen as a relatively appropriate level. In this regard, microwave power of 800 W, heating time of 3 min and sample mass of 90 g are relatively suitable for MHC of raspberry pulp under the current study. However, it should be noted that although MHC results in a significant loss of total anthocyanin content compared to untreated, this undesirable result still provides a valuable reference for future MHC of raspberry pulp to achieve high quality retention, e.g. laying the foundation for future temperature-controlled MHC of berry pulp.

In order to further reveal the relationship between concentration characteristics and quality attributes, the changes in water status and microstructures of raspberry pulp under microwave power of 800 W, heating time of 3 min and sample mass of 90 g are measured by LF-NMR and SEM, respectively, as shown in Figs. 5 and 6. From Fig. 5, the T_2 spectrum for raw raspberry pulp (before concentration) exhibited three relaxation periods as T_{21} (0.69–2.4 ms), T_{22} (6.82–15.7 ms), and T_{23} (67.48–204.91 and 714.94–1084.37 ms), representing three different water states in bound water, immobile water, and free water, respectively [35]. This indicates that the free

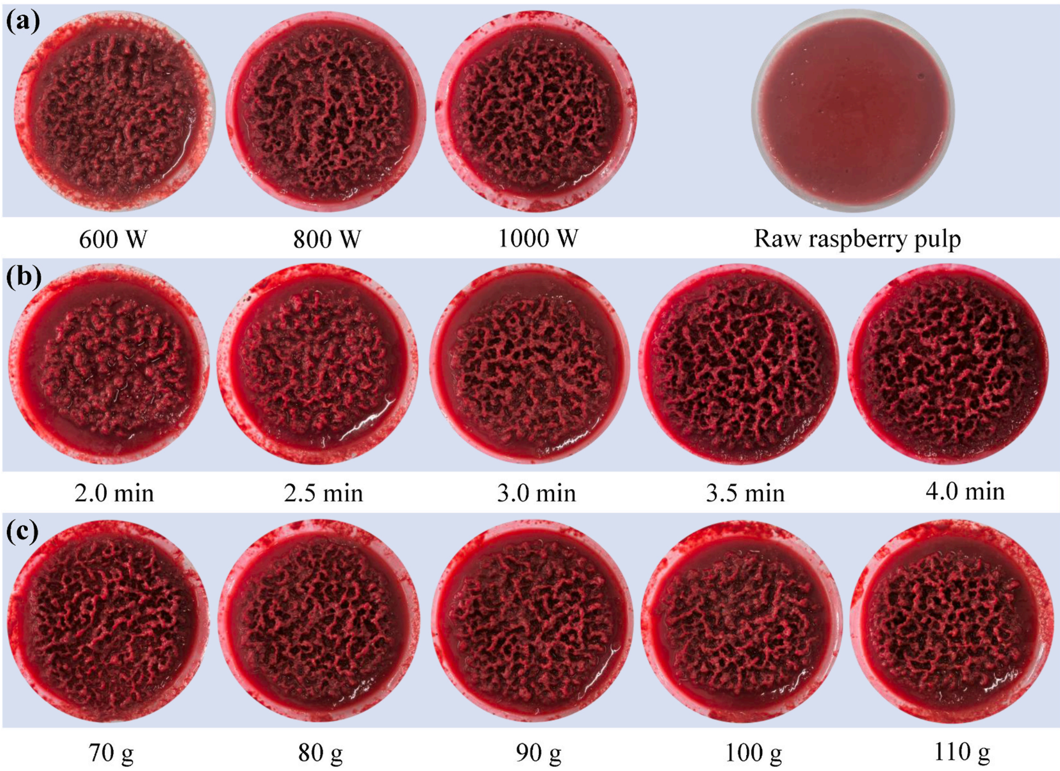

Fig. 4. Actual color appearance of the raspberry pulp under MHC at different processing variables (microwave power, heating time, and sample mass). **(a)** microwave power from 600 to 1000 W at a fixed heating time of 3 min and sample mass of 90 g, **(b)** heating time from 2 to 4 min at a fixed microwave power of 800 W and sample mass of 90 g, and **(c)** sample mass from 70 to 110 g at a fixed microwave power of 800 W and heating time of 3 min. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

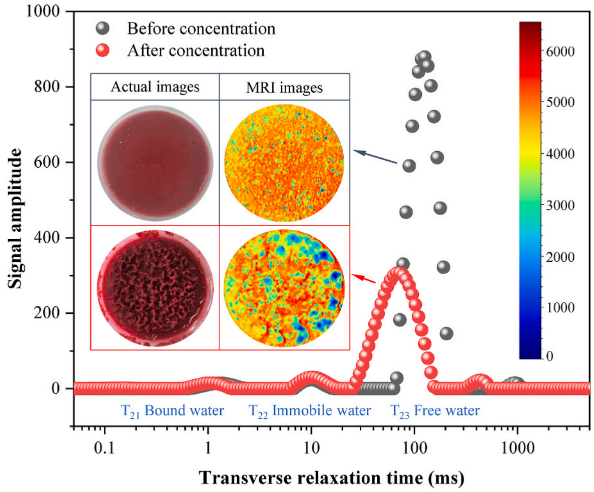

Fig. 5. Representative curve of transverse relaxation times (T_2) and MRI images of raspberry pulp. Note: 'Before concentration' represents the raw raspberry pulp, and 'after concentration' represents the raspberry pulp under the microwave power of 800 W, heating time of 3 min, and sample mass of 90 g.

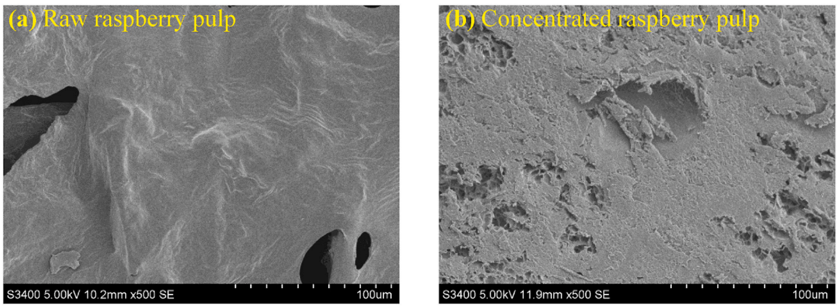

Fig. 6. Microstructure of (a) raw raspberry pulp and (b) concentrated raspberry pulp under the microwave power of 800 W, heating time of 3 min, and sample mass of 90 g.

water dominates the moisture content of the raspberry pulp as it has the highest signal amplitude of the peak in the T_2 spectrum representing the relative content of the moisture state [35]. After concentration by MHC, the T_2 peak began to shift to the left and the signal amplitude decreased as the unbound water gradually evaporated [36]. Furthermore, Fig. 5 also shows the corresponding MRI images of the raspberry pulp, where the red and blue colors represent high and low proton signal density, visualizing the evolution of water distribution in the blueberry pulp. For the raw raspberry pulp (before concentration), it has a uniform water distribution and high moisture content due to high signal intensity in the T_2 spectrum; after concentration by MHC, raspberry pulp has an uneven water distribution due to the non-uniformity of microwave heating [27], leading to the differences in quality attributes between different processing conditions. Fig. 6 intuitively shows the changes in the microstructure of the raspberry pulp with and without MHC through SEM images at a magnification of 500 ×. The microstructure in raw raspberry pulp (before concentration) is relatively dense and contains natural pores. Nevertheless, MHC treatment causes the changes of microstructure of raspberry pulp with many clear porous structures with small pores, which is caused by water migration pathways due to microwave heating [6]. Therefore, microwave heating causes the changes in temperature and moisture content to further affect the changes in total anthocyanin content and total color difference of the final product. This also confirmed the close relationship between concentration characteristics and quality attributes.

4. Conclusions

This study evaluated the concentration characteristics and quality attributes of raspberry pulp under microwave heating concentration at different microwave powers, heating times and sample masses. Increasing microwave power or heating time significantly accelerated water removal but had no significant effect on temperature, and decreasing sample mass resulted in rapid water removal but insignificant effect on temperature of raspberry pulp, while all these conditions resulted in loss of total anthocyanin content and deterioration of total color difference. LF-NMR and SEM results revealed that microwave heating caused the changes in temperature and moisture content to affect the total anthocyanin content and total color difference of the final product. The microwave power of

800 W, heating time of 3 min and sample mass of 90 g are relatively suitable for MHC of raspberry pulp. However, it should be noted that the results of this study may have certain limitations, as the experimental results are dependent on the microwave oven (brand and model), which is mainly due to the complex nature of microwave heating, as the transmission of electromagnetic fields depends on the structure of the microwave equipment. In addition, the raspberry pulp used in this study is frozen-thawed, which may differ from fresh raspberry pulp prepared from raspberries freshly picked or stored at 3–5 °C. Although there are some limitations mentioned, this study still improves the understanding of the concentration process and quality changes of raspberry pulp under microwave heating, and leads to the development of appropriate technology for MHC of berry pulp or juice.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Xinglong Zhao: Writing – original draft, Methodology, Conceptualization. **Haihui Zhu:** Visualization, Investigation. **Chenghai Liu:** Visualization, Formal analysis. **Liuyang Shen:** Writing – review & editing, Investigation, Formal analysis. **Xianzhe Zheng:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

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

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