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REGULAR PAPER

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Effects of vacuum soaking on the hydration, steaming, and physiochemical properties of japonica rice

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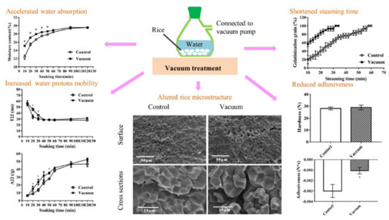
ABSTRACT

Soaking is an essential step in the processing of various rice products. In this study, the influences of vacuum soaking on hydration, steaming, and physiochemical properties of rice were investigated. Results showed that vacuum soaking accelerated water absorption as well as affected the mobility and density of water protons inside rice during soaking. Vacuum soaking could considerably shorten the optimal steaming time from 58 to 32 min and reduce the adhesiveness of steamed rice. Microstructure analysis of rice revealed that porous structure was formed on rice surface and the arrangement of starch granules became loosened after vacuum soaking. Moreover, vacuum soaking slightly reduced the relative crystallinity of rice starches without altering the crystalline type. The gelatinization temperature as well as the peak and trough viscosity was also decreased after vacuum soaking. Our study suggested that vacuum soaking was conducive to improve the soaking and steaming properties of rice.

Graphical Abstract



Vacuum soaking accelerated the hydration, shortened the steaming time, and affected the physiochemical properties of japonica rice.

Keywords: vacuum soaking, japonica rice, hydration, steaming time, physiochemical properties

Rice is the staple food of more than half the world's population, which provides energy and nutrients for human (Tong *et al.* 2019). With the development of economy, there are increasing kinds of processed rice food, such as rice wine, rice noodles, rice cakes, and so on. Soaking is an important procedure in the processing of rice products and it contributes to improve the processing characteristics of rice. Different products have different process requirements, and the purpose of soaking is also different. Some are to facilitate the steaming and cooking of raw rice like rice wine and instant cooked rice; others are to improve the

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efficiency of crushing, such as rice noodles, rice cakes, etc. However, soaking is always a time- and water-consuming procedure in rice food production. For instance, it takes about 2 days to soak rice in the traditional Chinese rice wine production (Jiao *et al.* 2017). It is meaningful to develop soaking methods to shorten soaking time, save energy, avoiding pollution, and improve the quality and yield of rice products as much as possible.

Vacuum treatment is a process in which materials are exposed to subatmospheric pressure, and the air inside the materials is removed. Vacuum impregnation has become a useful method for enriching fruits and vegetables with nutrients. This technique has been applied to produce calcium-fortified pineapples (Lima *et al.* 2016) or strengthen potato chips with antioxidants (Lopez and Moreira 2019). Royse *et al.* (2002) showed that vacuum soaking could reduce the soak time and improve the yield of wood chip shiitake. Furthermore, some researchers have applied vacuum treatment in the soaking of grains. Bello *et al.* (2008) revealed that the hydration rate of rice kernels increased with the decreasing of vacuum pressure in comparison with hydration at atmospheric pressure. Tian *et al.* (2014) studied the influence of soaking under different pressures on the hydration of rice grain and found that the hydration degree of normal rice was increased after vacuum soaking. Xiao *et al.* (2015) argued that the absorption of water and $NaHCO_3$ solution by soybeans was greater under vacuum and the hardness of soybeans was reduced. In addition, according to Loypimai *et al.* (2017) the application of NaCl-vacuum soaking could decrease the soaking time of parboiled glutinous rice and increased the concentrations of bioactive compounds in comparison with traditional method.

Although these pieces of evidence indicated vacuum soaking could increase water absorption velocity of grains, how vacuum soaking affects water absorption, particularly about the water state of rice during soaking remains unclear. Moreover, little research investigated the effect of vacuum soaking on the steaming properties of rice and physicochemical properties of rice flour. The present study aimed to investigate the effect of vacuum soaking on the hydration, steaming, and physiochemical properties of rice. The moisture content, the mobility of water protons, the microstructure changes, the relative crystallinity, the gelatinization properties, and pasting properties of rice were evaluated to discuss the effect of vacuum soaking on rice. The characteristics of steamed rice, such as hardness, adhesiveness, springiness, and cohesiveness, were also determined after vacuum soaking.

Materials and methods

Materials

The rice used in the experiment was milled japonica rice cultivated in Northeast of China, produced by Yihai Kerry Grain and Oil Food Industry Co. All the samples were packed in low-density polyethylene bags and stored in a refrigerator at 4 °C. Prior to the experiment, the stored grains were allowed to equilibrate at ambient temperature. The moisture content of rice was 13.20%, determined in an oven at 105 °C.

Vacuum soaking and moisture content measurement

Ten grams of rice samples were placed into glass suction filter containers with 40 mL distilled water (20 °C), and then soaked under vacuum condition of 0.09-0.1 MPa below atmospheric pressure (approximately 0.01 MPa) or under regular atmospheric pressure of approximately 0.1 MPa at room temperature. The vacuum condition was provided by a water circulating vacuum pump (SHZ-D [III], Shanghai Yuhua Instrument Equipment Co., Ltd., Shanghai, China). After soaking for 10, 20, 30, 40, 50, 60, 90, and 120 min (Huang *et al.* 2009; Tomita *et al.* 2019), rice samples were immediately isolated from water and wiped with filter paper to remove the surface water, and then weighted to an accuracy of ±0.0005 g. After that, the samples were dried to a constant weight at 105 °C in an oven (DHG-9070, Shanghai Yiheng Technology Co., Ltd., Shanghai, China). The moisture content was calculated as eqn (1):

$$\text{moisture content}(\%) = (m_0 - m_t)/m_0 \times 100\%, \tag{1}$$

where m_0 is the weight of the sample after soaking (g), and m_t is the weight of the soaked sample after drying (g).

LF-NMR measurement

The water proton dynamics of rice during vacuum soaking process was analyzed through low-field nuclear magnetic resonance (LF-NMR) using a 23.217 MHz (0.55 T) NMR analyzer (PQ001, Niumag Co., Ltd., Shanghai, China). After soaking, the rice samples were isolated, and surface moisture water was wiped off with an absorbent paper. Approximately 2.0 g soaked rice samples were placed into a 15 mm NMR tube, which was sealed by a preservative film to prevent water evaporation. The tube was then placed in a 32 °C water bath for 20 min and inserted into the NMR probe. The free induction decay sequence was used to determine the central frequency and 90 pulse width of proton NMR, and the spin–spin relaxation time (T2) of the sample was measured through Carr–Purcell–Meiboom–Gill sequence. Each sample was processed 9 times, and MultiExp Inv Analysis software was used for nuclear magnetic data inversion.

Total solids leaching

The amount of total leached solids during soaking was measured following the procedure of Li *et al.* (2019) with some modifications. The soaking water was transferred to a 50 mL centrifuge tube. After being centrifuged for 10 min with RCF of 3040 *g*, the supernatant was removed. The precipitate was dried and the amount of total leached solids was weighed through constant weight method at 105 °C. Results were presented as g of solids per 100 g of dry grain. All experiments were made at least in triplicate.

Optimal steaming time

The optimal steaming time of rice was evaluated in accordance with the national standard ISO 14864 (ISO 1998; Rice—Evaluation of gelatinization time of kernels during cooking) with minor modifications. Rice was soaked under vacuum or regular atmospheric condition for 120 min, then was separated from the water, placed in the sampling cylinder (diameter: 50 mm, height: 20 mm) on a steaming basket with 4 layers of gauze, and steamed with water vapor using a steam boiler (MZ-ZG26Easy401, Midea Group, Guangdong, China). After steaming for 10 min, sampling cylinder was taken out every 2 min. Ten intact rice kernels were randomly selected from the same layer without touching the inner wall (8 mm under the surface) of sampling cylinder every time and then cut off using a sharp blade (Miao *et al.* 2016). Rice with no white spot inner was considered to be fully gelatinized. The time at which 100% of grains reached the gelatinized state was identified as the optimal steaming time. All the above measurements were performed 4 times.

Textural characteristics of steamed rice

The textural properties of steamed rice samples steamed with optimal steaming time were measured using a texture analyzer (TA.TOUCH, Shanghai Bosin Industrial Development Co., Ltd., Shanghai, China). The sample grains were randomly selected from the same layer without touching the inner wall of the cylinder (10 mm under the surface) after steaming (Miao *et al.* 2016). Rice sample was placed on a baseplate at the center of the probe and compressed using a 36 mm diameter probe. The pretest, test, and posttest speeds were set at 1, 0.5, and 1 mm/s, correspondingly. The compression distance was 75%, and the trigger force was 0.049 N. The measure of each group was repeated at least 15 times with different grains, and completed within 20 min to maintain the similar moisture content among samples. Each result comprised the average value of the test with maximum and minimum values removed (Zhang *et al.* 2015). The experiments were performed in triplicate and the data were analyzed using SPSS system v.17.0 (SPSS Inc., Chicago, IL, USA).

Scanning electron microscopy

The morphological properties of rice were measured through the method of Yu *et al.* (2017). Raw rice soaked for 120 min or steamed rice of optimal steaming time were dried by a vacuum freeze dryer (SCIENTZ-10N, Ningbo Scientz Biotechnology Co., Ltd., Ningbo, China). After drying, the grains were cut off along the central axis using a sharp blade, stuck on a specimen holder and coated with a thin film of gold in a vacuum evaporator. The surface and cross section of rice kernel were observed and photographed using a scanning electron microscope (Quanta-400, FEI Company, America) with a voltage of 20.00 kV.

XRD

After soaking for 120 min under vacuum or atmospheric pressure, rice samples were dried with a vacuum freeze dryer, and ground into powder using a disc mill (LFP-4000, Filibo Industrial Co., Ltd., Shanghai, China). The rice flour was then passed through a 75 µm screen. The X-ray diffraction (XRD) patterns of samples were determined using an X-ray diffractometer (D8 Advance, Bruker AXS GmbH, Germany) operating at a voltage of 40 kV, a current of 40 mA, and Cu Kα radiation of $\lambda = 0.15418$ nm. The samples were scanned in 2θ ranging from 5° to 30° with a sampling width of 0.02° at a scan rate of 6°/min (Lopez-Rubio *et al.* 2008). Each sample was measured 3 times. The relative crystallinity of an XRD spectrum was calculated through the curve plot method using MDI-Jade 6.0 software in accordance with eqn (2).

$$X_c\,(\%) = A_c/(A_a + A_c) \times 100\%, \tag{2}$$

where X_c was the relative crystallinity of the sample; A_c and A_a were the areas of crystalline and amorphous regions, correspondingly, in the diffractogram (Chen *et al.* 2018).

Gelatinization properties analysis

A differential scanning calorimeter (2Pyris Diamond, Perkin Elmer, USA) was used to determine the gelatinization properties of rice flour prepared from 120 min-soaked rice, according to Zhong *et al.* (2013) with some modifications. Rice flour (2.5 mg, dry weight basis) was accurately weighed and placed into a liquid aluminum pan, and 7.5 µL distilled water was added. The pan was hermetically sealed, equilibrated for 3 h at ambient temperature, and scanned from 20 to 90°C at a heating rate of 10°C/min with a sealed empty liquid aluminum pan as reference. The onset (T_o), peak (T_p), and conclusion (T_c) temperatures and gelatinization enthalpy (ΔH) of gelatinization were determined using Pyris Manager data processing software. Experiments and analyses were performed in triplicate.

Pasting properties

The pasting properties of rice flour prepared from 120 min-soaked rice were characterized using a SmartStarch analyzer (MCR92/102, Anton Paar Co. Ltd, Austria). Rice flour (3.00 g, 12% moisture basis) was mixed with 25.0 mL of distilled water in an aluminum canister. The heating and cooling cycle was programmed as follows: the sample was held at 50 °C for 1 min, then heated to 95 °C within 3.75 min, and held at 95 °C for 2.5 min. It was then subsequently cooled to 50 °C within 3.85 min, and held at 50 °C for 1.4 min. Peak viscosity (PV), trough viscosity (TV), breakdown (BD), final viscosity (FV), and setback (SB) were recorded.

Statistical analysis

All data were analyzed using SPSS system v.17.0 (SPSS Inc., Chicago, IL, USA), and the result was shown as mean standard deviation. Pearson's correlations between moisture content and the density of water protons were analyzed.

Results and discussion

Vacuum soaking increased the water absorption rate of rice

The effect of vacuum soaking on the moisture content was illustrated in Figure 1a. The moisture content of rice soaked under vacuum condition was significantly ($P < .05$) higher than that soaked under regular atmospheric pressure before 50 min, and reached equilibrium at 90 min. The initial rapid water absorption under vacuum may result from the hydrodynamic mechanism (Fito *et al.* 1996): after starting the vacuum pump, the air trapped in the rice was removed gradually, and the rice took up water rapidly by differential pressure between inside and outside of rice and capillary action. At 120 min, the moisture content of rice under atmospheric pressure was the same as that under vacuum. This indicated that vacuum soaking could accelerate the water absorption rate in comparison with soaking at atmospheric pressure, but it was unable to promote water absorption capacity of rice, which corresponded well with the report of Bello *et al.* (2008).

The effect of vacuum soaking on total solids leaching of rice was depicted in Figure 1b. The amount of total leached solids was significantly ($P < .05$) higher in the vacuum-soaked group than in the control group during the soaking process. In the early stage of vacuum soaking, we observed that many small bubbles were continuously generated on the surface of the rice grains, suggesting that the air inside the rice grains was constantly taken away. Thus, the increasing of total solids leaching of vacuum-soaked group might be due to the gas expansion as

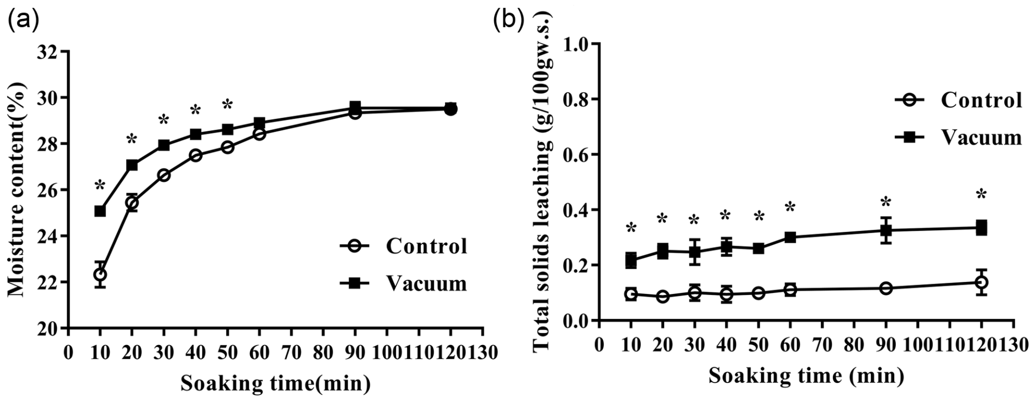

Figure 1. Effect of vacuum soaking on moisture content and total solids leaching of rice. (a) Moisture content; (b) total solids leaching. Number of replications (*n*), $n \geq 3$. * represents $P < .05$.

previously reported (Occhino *et al.* 2011), thus more solids flowed out from the surface of the rice grains.

Vacuum soaking promoted water hydration properties of rice as revealed by LF-NMR analysis

The LF-NMR analysis was performed to investigate the influence of vacuum soaking on rice hydration properties. Relaxation time T2 indicates the fluidity of water protons, whereas the corresponding relaxation signal component A2 indicates the density of water protons (Srikaeo and Rahman 2018). According to previous reports, there are 3 kinds of water in rice: the fastest fraction is T2b, with relaxation time ranging from 0.01 to 1 ms, regarded as strongly bound water; the intermediate fraction is T21, with relaxation time ranging from 1 ms to 10 ms, assigned as moderately bound water; the slowest fraction is T22, with relaxation time ranging from 10 ms to 100 ms, assigned as free water (Li *et al.* 2015; Hu *et al.* 2019; Zhu *et al.* 2019).

T2b represents the relaxation time of protons trapped within macromolecules (starch and protein) (Li *et al.* 2019). In the initial 30 min, the relaxation time T2b (Figure 2a) was increased with the elongation of soaking time, and the corresponding proton density A2b (Figure 2b) decreased. After soaking for 30 min, no significant change was observed between the vacuum-soaked group and the control in T2b and A2b of the strongly bound water. As presented in Table 1, the density of strongly bound proton showed a negative correlation with the moisture content. So we speculated that the infiltration of external water might affect the degree of bonding between water protons and macromolecules, thus part of strongly bound water might be converted into moderately bound water protons or other status.

The moderately bound water protons not only included intragranular confined water that is exchangeable with outside water slowly but also exchangeable protons of amylopectin and glutelin (Tang *et al.* 2001). When the rice was soaked under vacuum for 10 min, the values of T21 (Figure 2c) and A21 (Figure 2d) were significantly ($P < .05$) higher than that of control group. The change of moderately bound water protons was caused by rapid infiltration of water because the moisture content of vacuum-soaked rice was 25.08%, which was 12.36% higher than that of control group (22.32%), as shown in Figure 1a. The corresponding proton density A21, representing the major fraction of water proton, increased faster in the vacuum-treated group than in the control group and reached a peak at 30 min (Figure 2d), which showed a positive correlation with the moisture content (Table 1). These results implied that vacuum soaking could accelerate the penetration of water giving more free water to bind with the macromolecules such as amylopectin and glutelin, and therefore the fluidity of water protons was enhanced and the proton density A21 was increased (Li *et al.* 2015).

T22 represents the relaxation time of free water protons existed in the extragranular space between closely packed granules. Relaxation time T22 showed a conspicuous ($P < .05$) decreasing trend and reached a plateau at 20 min in the vacuum-treated group while at 40 min in the control group (Figure 3e). The corresponding proton density A22 (Figure 3f) increased gradually with the soaking time, and the values of A22 were higher ($P < .05$) in the vacuum-soaked group than in the control group. Correlation analysis (Table 1) showed that the density of weakly bound proton was related to moisture content. These results suggested that vacuum soaking might introduce more water into the interstitial space of the granules and weaken the interaction between biopolymers and water molecules, thereby reducing the fluidity of free water protons.

Vacuum soaking shortened the steaming time of rice and diminished the adhesiveness of steamed rice

The water absorption curve showed that the moisture content of rice soaked under atmospheric pressure was identical with that soaked under vacuum at 120 min (Figure 1a), which meant the moisture content nearly reach saturation. Therefore, the rice soaked for 120 min was used to determine the steaming time. The effect of vacuum soaking on the gelatinization of rice with different steaming times was displayed in Figure 3a. For the atmospheric pressure-soaked rice, the time for 100% of grains to reach the gelatinized state was 58 min. However, 100% of the vacuum-soaked rice reached the gelatinized state in only 32 min. The optimal steaming time of vacuum-soaked rice (32 min) was substantially shorter than that of atmospheric pressure-soaked rice (58 min). According to Tian *et al.* (2014), we presumed that vacuum soaking could accelerate the infiltration of water and make the water distribute more evenly, which may be contribute to the gelatinization of starch, thereby resulting in the reduction of steaming time of rice.

The textural properties of steamed rice were also analyzed. As presented in Figure 3b, there was no significant difference

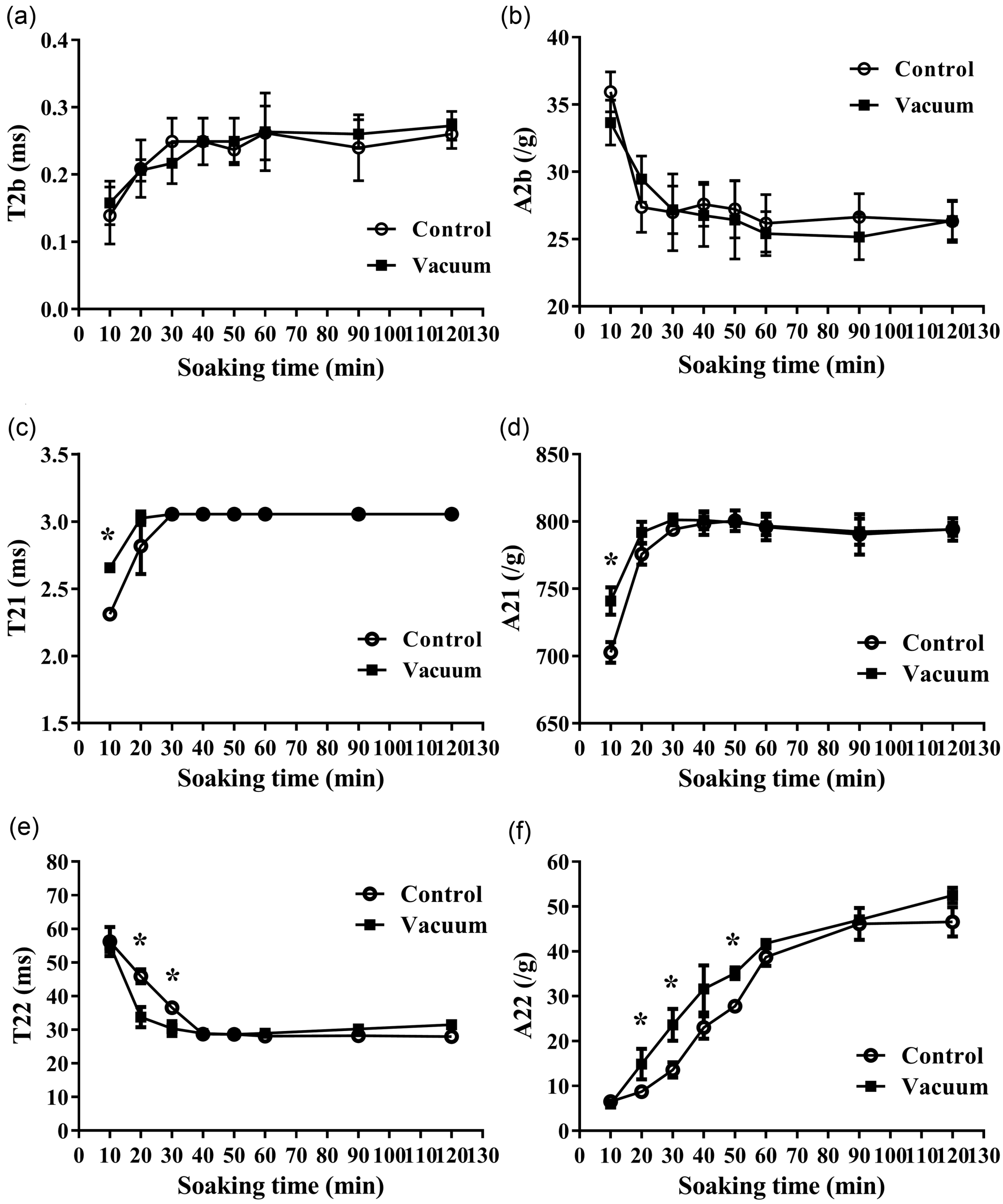

Figure 2. Effect of vacuum soaking on water protons dynamics of rice. (a) Relaxation time of strongly bound proton; (c) relaxation time of moderately bound proton; (e) relaxation time of weakly bound proton; (b) proton density of strongly bound proton; (d) proton density of moderately bound proton; (f) proton density of weakly bound proton. * represents $P < .05$.

Table 1. The Pearson correlation coefficients between the moisture content and the density of water protons

Moisture content	A2b	A21	A22
Control	−0.800**	0.896**	0.836**
Vacuum	−0.833**	0.855**	0.874**

A2b, proton density of strongly bound proton; A21, proton density of moderately bound proton; A22, proton density of weakly bound proton; **, correlation is significant at the .01 level (2-tailed).

in hardness between vacuum-soaked rice and regularly soaked rice, but the adhesiveness of vacuum-soaked rice was significantly ($P < .05$) lower than that of regularly soaked rice. Li *et al.* (2017) proposed a molecular structural mechanism that the increase of the amount of amylopectin, the proportion of short amylopectin chains and the amylopectin molecular size on the surface of steamed rice could affect the molecular interactions leading to increased stickiness of steamed rice. Based on our observations that vacuum soaking resulted in more leached solids (Figure 1b) which might contain not only short chain starches but also those starch granules attached on the rice surface, we conjectured that the lower adhesiveness of vacuum-treated rice might owe to the more leached solids during vacuum soaking which resulted in less short chain and surface attached amylopectins. Cohesiveness was used to express the size of the binding force inside the steamed rice. Our results showed that vacuum soaking did not alter the cohesiveness of rice. In addition, the springiness of rice was also unaffected through vacuum soaking.

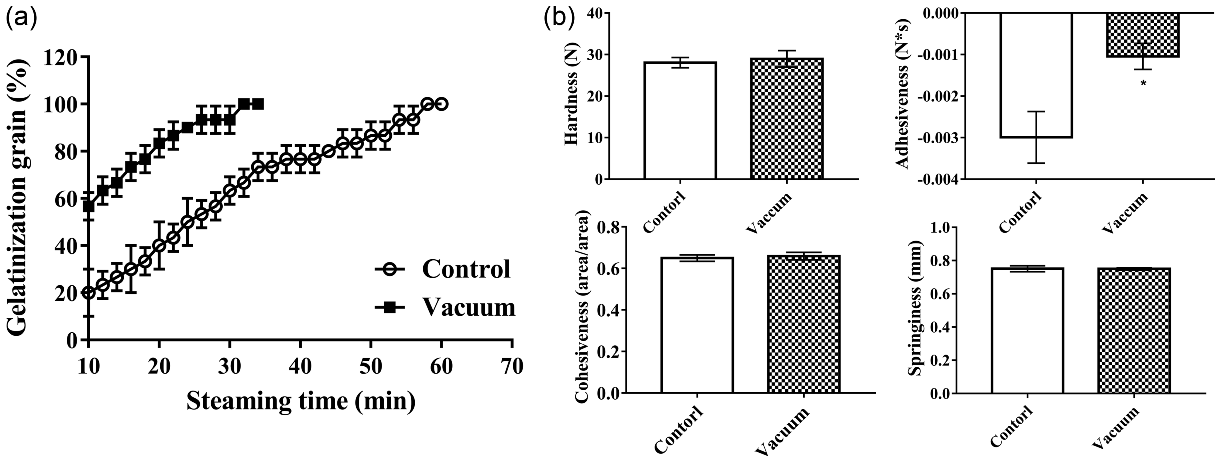

Figure 3. Effect of vacuum soaking on the optimal steaming time and textural characteristics of steamed rice. (a) Gelatinization grains of streamed rice with different steaming times; (b) textural characteristics of steamed rice. * represents $P < .05$.

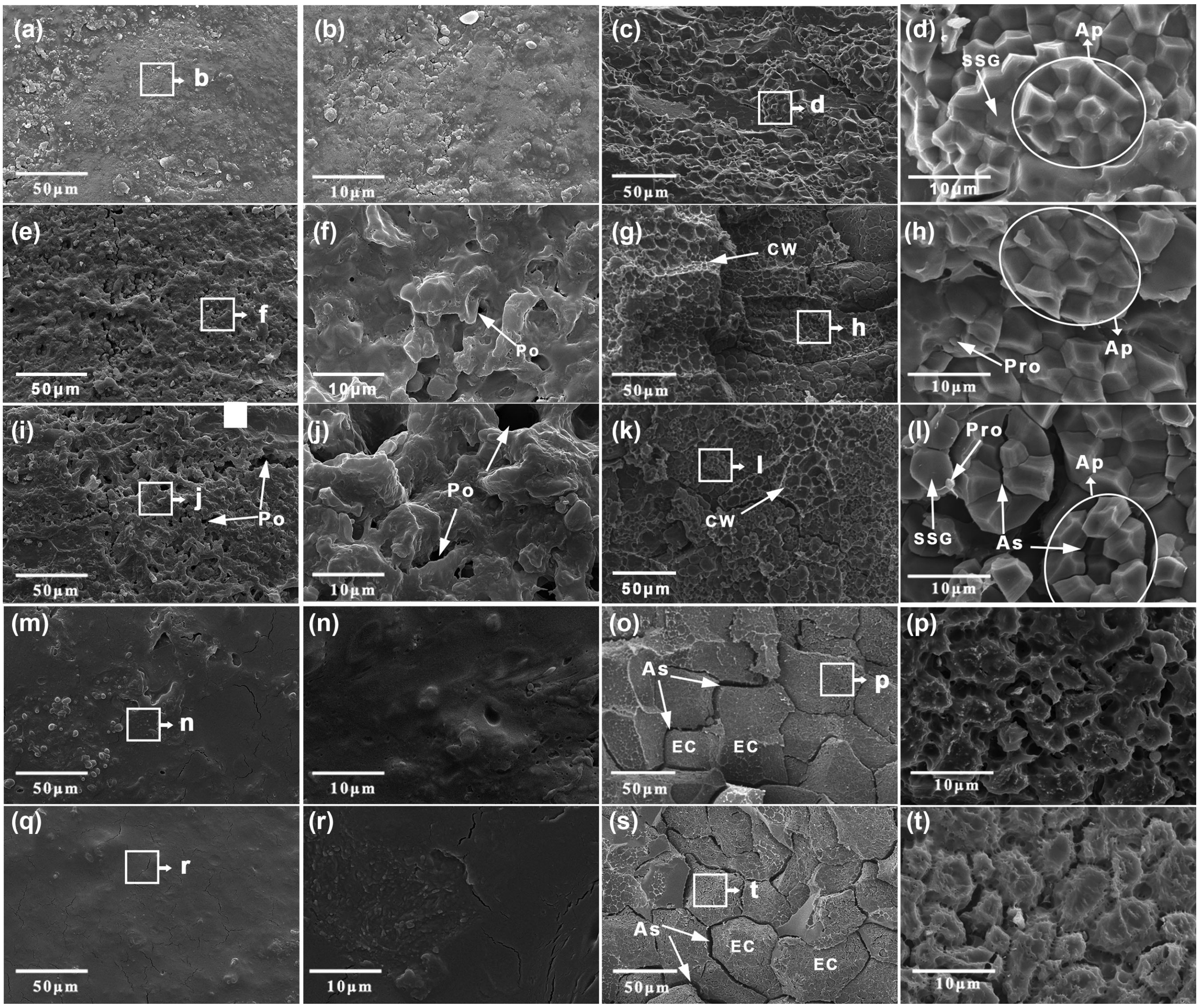

Figure 4. SEM micrographs of the surface and cross sections of rice grains. (a-d) raw rice; (e-h) atmospheric pressure-soaked rice; (i-l) vacuum-soaked rice; (m-p) steamed rice with regular atmospheric pressure soaking; (q-t) steamed rice with vacuum soaking. Po, pore; SSG, single starch granule; Ap, amyloplast; Pro, protein; As, airspace; EC, endosperm cell; CW, cell wall. (a, e, i, m, q) Surface sections in 2000× (scale bar = 50 μm); (b, f, j, n, r) surface sections in 10 000× (scale bar = 10 μm); (c, g, k, o, s) cross sections in 1000× (scale bar = 50 μm); (d, h, l, p, t) cross sections in 7500× (scale bar = 10 μm).

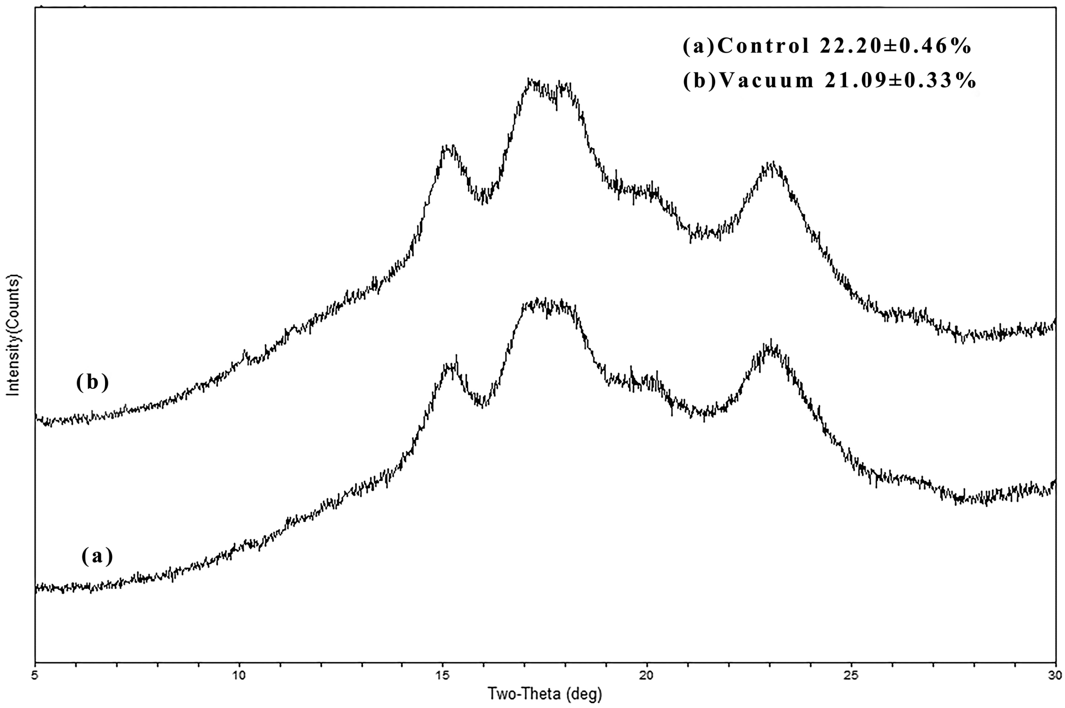

Figure 5. XRD patterns of rice flour. (a) XRD graph of the atmospheric pressure-soaked rice flour; (b) XRD graph of the vacuum-soaked rice flour.

Effect of vacuum soaking on the microstructure of rice

The morphological characteristics of raw rice and those obtained after vacuum soaking and steaming were demonstrated in Figure 4. The surface of raw rice (Figure 4a and b) was smooth, dense, and free of pinhole porosity but became rough and porous after soaking (Figure 4e and f). When soaked under vacuum condition, the surface of soaked rice (Figure 4i and j) became more roughly and unevenly, with additional cracks appeared and many small pores formed. In the initial stage of vacuum soaking, we observed that air bubbles continued to emerge on the surface of rice grains, which might contribute to the formation of porous structures on the surface. The surface microstructure of steamed rice with vacuum soaking was smoother than that of control rice (Figure 4m, n, q, and r). This result supported the speculation that less surface attached starch granules might lead to lower adhesiveness of vacuum-soaked rice (Figure 3b).

As shown in Figure 4c, d, g, h, k, and l, we could observe single starch granules (polygonal granules), amyloplasts, and protein granules (small spherical), which are reported to form the endosperm cell together (Zhu *et al.* 2019). The starch granules and amyloplasts of raw rice were polygons and tightly arranged (Figure 4c and d) which was similar to the report of Leethanapanich (Leethanapanich *et al.* 2016). The microstructure of the cross sections showed that soaking led to the swelling of single starch granules and amyloplasts (Figure 4g and h), which was also reported by previous studies (Kang *et al.* 2006). Vacuum soaking not only exacerbated starch particles swelling but also loosen the arrangement of starch particles in amyloplasts causing the disintegration of starch granules from amyloplasts (Figure 4k and l). For the steamed rice, there were airspaces between the endosperm cells (Figure 4o and p). The morphology of single starch granule and amyloplast was changed, and flocculent fluffy substances with fine voids were formed around the granules periphery (Figure 4s and t), which might resulted from the swelling and gelatinization of starch (Ogawa *et al.* 2003).

Table 2. Effect of vacuum soaking on the gelatinization properties of rice flour

	T_o (°C)	T_p (°C)	T_c (°C)	ΔH (J/g)
Control	54.69 ± 0.23^a	61.22 ± 0.08^b	67.70 ± 0.05^b	8.94 ± 0.12^a
Vacuum	54.15 ± 0.09^a	59.98 ± 0.10^a	67.18 ± 0.03^a	8.81 ± 0.07^a

All values are given as means ± SD. Means in the same columns with different letters are significantly different ($P < .05$). T_o, onset temperature; T_p, peak temperature; T_c, conclusion temperature; ΔH, gelatinization enthalpy.

Influence of vacuum soaking on the relative crystallinity of rice

The XRD patterns of rice were plotted in Figure 5. Both of atmospheric pressure-soaked rice and vacuum-soaked rice displayed a typical pattern with main reflections at $2\theta = 15.1°$, 17.0°, 18.1°, and 23.0°, which were close to the A-type diffraction with strong peaks at $2\theta = 14.2°$, 17.4°, 18.7°, and 23.4° (Srikaeo and Rahman 2018), thereby suggesting that vacuum soaking retained the crystalline type of rice. However, the relative crystallinity of vacuum-soaked rice was 21.09 ± 0.33%, which was lower ($P < .05$) than that of the atmospheric pressure-soaked rice (22.20 ± 0.46%). This result suggested that vacuum soaking could disrupt the crystalline of starch granules, which was consistent with previous report that vacuum soaking allowed water molecules to enter into the rice granules quickly, leading to loosened starch granules and thereby possibly opened and weakened the double helices of the starch crystalline region and reduced the relative crystallinity (Meng *et al.* 2018). In addition, the relative crystallinity of rice not only depends on the crystallinity of rice starch but is also related to proteins and lipids (Yu *et al.*

Table 3. Effect of vacuum soaking on the pasting properties of rice flour

	PV (RVU)	TV (RVU)	FV (RVU)	BD (RVU)	SB (RVU)
Control	320.84 ± 11.75^{b}	177.5 ± 4.89^{b}	267.51 ± 3.51^{a}	129.23 ± 4.95^{a}	116.49 ± 5.26^{a}
Vacuum	273.1 ± 9.25^{a}	152.02 ± 3.51^{a}	273.41 ± 4^{a}	122.87 ± 5.06^{a}	108.89 ± 4.07^{a}

All values are given as means ± SD. Means in the same columns with different letters are significantly different ($P < .05$). PV, peak viscosity; TV, trough viscosity; BD, breakdown; FV, final viscosity; SB, setback.

2012). The decrease in relative crystallinity of vacuum-soaked rice might be also related to increased total leached solids, which contain starch, lipids, and proteins.

Vacuum soaking altered the gelatinization properties of rice

The effect of vacuum soaking on the gelatinization properties (T_o, T_p, T_c, and ΔH) of rice was summarized in Table 2. The thermal transition temperatures T_p and T_c were lower ($P < .05$) in the gelatinization of vacuum-soaked rice than in atmospheric pressure-soaked rice. It was reported that the disruption of crystalline region of starch granules resulted in the decrease of gelatinization temperature and ΔH (Yu *et al.* 2015; Meng *et al.* 2018), and some of the double helix structure in amorphous regions would degrade faster and greater under vacuum soaking (Zhang *et al.* 2018). In our study, the decrease of T_p and T_c was consistent with the XRD spectra (Figure 5), in which the crystallinity of the vacuum-soaked rice was reduced in comparison with the atmospheric pressure-soaked rice. Thus, our result indicated that vacuum soaking may affect the gelatinization properties of rice by decreasing the crystallinity of rice.

Vacuum soaking altered the pasting properties of rice

The pasting properties of rice flour soaked under regular atmospheric pressure and vacuum condition are presented in Table 3. Result showed that vacuum soaking significantly ($P < .05$) reduced the peak viscosity and trough viscosity compared to the control group. Nawaz *et al.* (2018) suggested that the gelatinization of starch led to a decrease in peak viscosity. In this study, the drop of peak viscosity of vacuum-soaked group could be attributed to the decrease of peak temperature and conclusion temperature of gelatinization (Table 2). The reduction of peak viscosity is reported to result from structure destruction of starches (Li *et al.* 2012; Zhi *et al.* 2016), while we also observed disrupted structure of amyloplasts after vacuum soaking (Figure 4l) which may result in peak viscosity declined.

Conclusion

We verified the effects of vacuum soaking on the water hydration properties, steaming properties, and physiochemical properties of rice in this study. Our results suggested that vacuum soaking could accelerate the hydration of rice by removing air trapped inside rice quickly so that porous structure formed on rice surface and the channels formed inside the rice became wider, which would be conducive to the infiltration and diffusion of water. We also found that the optimal steaming time was greatly shortened from 58 to 32 min after vacuum soaking, and the adhesiveness of steamed rice was significantly lower than that of control rice. Physiochemical analysis indicated vacuum soaking could loosen the starch granules causing the disintegration of starch granules from amyloplasts, decrease the relative crystallinity, lower the gelatinization temperatures, and reduce the peak and trough viscosity of rice flour. Therefore, vacuum soaking could be a promising technique for the processing of rice productions such as rice wine, convenient rice, rice noodles and so on, which have specific requirement of soaking and steaming quality of rice, as it could not only saved time but also promote the quality characteristics of rice. However, the effect of vacuum soaking on the quality of specific products should be studied further.

Author contribution

Q.L.: Investigation, writing—original draft and review; S.L.: methodology, writing—review and editing; X.G.: conceptualization, supervision, and funding acquisition; K.H.: validation, writing—review and editing; F.Z.: data curation.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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