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Effects of Ultrasound and Steam Explosion Treatments on the Physicochemical Properties of Rice Bran Fibre

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ABSTRACT

Rice bran (RB) is an underutilised fibre source due to undesirable effects when incorporated into food products. Thus, this study aims to improve the physicochemical properties of RB by using ultrasound (US) and steam explosion (SE) treatments, making it more usable in food applications. The US treatment of unpurified RB resulted in inconsistent average particle size, water binding capacity (WBC), and swelling capacity (SC). The bulk density (BD) decreased while the oil binding capacity (OBC) increased as the amplitude and time increased. While the purified rice bran resulted in decreased average particle size and BD; and increased WBC, SC, and OBC. The surface microstructure of the unpurified and purified rice bran became more porous, and the colour of the RB was darkened proportionally to the intensity of US treatment. The average particle size of unpurified increased while the purified RB increased after steam explosion treatment regardless of the intensity. The SE treatment also decreased WBC and SC of unpurified and purified RB, but no changes were observed on the surface microstructure of both samples. The BD of unpurified RB decreased, while the BD of purified RB increased after SE treatment. The SE treatment also resulted in a decrease in the OBC of purified RB, but no significant ($p > 0.05$) improvement was observed in the OBC of unpurified RB. Ultrasound brought these changes in the two treatments more effectively than steam explosion. The alteration of physicochemical properties of RB by the US and SE treatment in this study will allow it to be more applicable in the formulation of food products.

Keywords: Fibre, physicochemical, pretreatment, rice bran, steam explosion, ultrasound

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INTRODUCTION

Rice bran is a by-product of the rice milling industry and is currently underutilised. Rice bran oil is the main product that has been commercialised, while some fat-free rice bran is utilised as stockfeed (Chinma et al., 2015; Ghosh, 2007). Currently, other uses of rice bran include nutritional supplements and ingredients of microbiological media (Hansawasdi & Kurdi, 2017; Sharif et al., 2014). Like other cereal bran, rice bran is rich in dietary fibre, as it contains up to 35% on a dry matter basis (Daou & Zhang, 2012). However, despite its high dietary fibre content, limited research has explored the functional properties of rice bran fibre, Even less research has attempted to improve its physicochemical and functional properties.

Studies showed that the incorporation of rice bran in the bread formulation led to a decrement in bread volume and had a detrimental effect on the texture and colour of the bread (Sharif et al., 2014). Physicochemical properties, such as bulk density, particle size, surface area, water binding capacity, swelling capacity, fat binding capacity, and solubility of rice bran fibre, play important roles in the processing and sensory properties of the products in which the fibre is incorporated. They can also significantly affect the health-related physiological functions of rice bran. Several studies have reported that chemical, physical, and enzymatic treatments can modify and improve the physicochemical properties of rice bran fibre (Daou & Zhang, 2011; Lebesi & Tzia, 2012; Qi et al., 2016; Rafe et al., 2017). Physical treatments offer many advantages over chemical treatments, such as lower costs, environmental friendliness, and industrially more practical (Brodeur et al., 2011). Among the physical treatments, ultrasound and steam explosion are particularly noteworthy for their ability to disrupt and breakdown the polymeric structure of cereal bran fibre, whereby increasing the fibre solubility by generating soluble oligosaccharides and enhancing the technological and health functionalities of the fibre (Daou & Zhang, 2012; Jiang & Guo, 2016).

However, the effects of ultrasound (US) and steam explosion (SE) treatments on the physicochemical properties of rice bran fibre have rarely been studied extensively. Furthermore, it has been reported that the purity of bran fibre may impact the effectiveness of some physical treatments due to the presence of starch and protein in the fibre in native bran (Qi et al., 2015), but these aspects have not been properly examined for US and SE treatments of rice bran. Ultrasound treatment is hypothesised to be able to breakdown the rice bran fibre caused by the acoustic cavitation where the microbubbles produced by ultrasound collided with the fibre, collapsed, and produced immense local energy, while the SE treatment is believed to degrade the lignocellulosic material of the rice bran due to the use of high temperature and pressure with a sudden release of the pressure. Therefore, both treatments are expected to alter the physicochemical properties of rice bran fibre.

Therefore, the objectives of this study were to assess the effect of US and SE treatments on the physicochemical properties of rice bran fibre with respect to the purity of the rice bran. In addition, this study also will provide evidence on how ultrasound and steam explosion treatments may improve the physicochemical properties of rice bran fibre for future use in food products.

MATERIALS AND METHODS

Rice Bran Samples, Chemicals, and Materials Used

Rice bran (RB) used in this study was obtained from SunRice (Australia). Upon collection from the milling and polishing process, the RB was stabilised by heat-treatment (drum dryer) and, after cooling to room temperature (25 ± 2 °C), packed in sealed polyethene bags with a brown paper outer cover. Following that, the bran samples were kept in containers packed with ice blocks for approximately 24 h during transportation to our laboratory at The University of New South Wales, Sydney, Australia. After arriving at the laboratory, the RB was vacuum-packed in 500 g polyethene bags and stored at -18 ºC before use. Ethanol and *n*-hexane were purchased from Ajax Chemical Pty. Ltd. (Australia). Corn oil was purchased from local supermarkets. Water used in all experiments was purified by reverse osmosis using the Mili-Q® reverse osmosis (RO) system (Australia) and henceforth referred to as Mili-Q® water.

Defatting and Purification of Rice Bran

RB defatting was done following the procedure of Uraipong and Zhao (2016) with a minor modification. Firstly, the RB was dispersed in *n*-hexane (1:5, w/v), mixed in an incubator shaker at 250 rpm for 20 min, followed by centrifugation (Avanti J. E. Centrifuge Series, Beckman Coulter, USA) at 9,600 x *g* for 20 min and the *n*-hexane decanted. This procedure was repeated twice, and the defatted RB was first air-dried in a fume hood overnight to remove residual hexane by evaporation. Next, the bran samples were dried at 60 ºC overnight in an oven and finally stored in sealed polyethene bags at 4 °C before purification. Finally, purifying RB fibre was done by removing starch and protein following the procedure described by Hu et al. (2015) with minor modifications.

Physical Pretreatment of Rice Bran

Physical treatment of RB involved two treatments, which were ultrasonic cavitation and steam explosion.

Ultrasound Cavitation. Ultrasound (US) cavitation treatment was applied to defatted and purified RB using a sonication immersion probe (20 kHz and 450 W, Branson Sonifier 450, USA). Defatted RB was dispersed in water at a ratio of 1:30 w/v in a 250 mL beaker, and the treatment was performed at three different power amplitudes, 60%, 80%, and 95%, and for 5, 10, 15, and 20 min for each power setting. The beaker containing the sample was partially immersed in an ice water bath

to ensure that the samples did not become overheated. The temperature of the slurry during the treatment was maintained at 25 ± 5 °C. The sonicated samples were freeze-dried (Leybold Lyovac GT2, Germany), sieved to pass 450 µm mesh size, and the samples were stored at -18 °C until further analysis. The freeze-dried RB was manually crushed with a spatula instead of grinding before sieving to prevent any additional mechanical effect on the RB fibre properties.

Steam Explosion. Instant catapult steam explosion treatment (SE) of the bran samples (defatted and purified RB) was performed using a QBS-80 batch SE apparatus (Hebi Steam Explosion Research Centre, China). Bran samples (50 g) were treated at 0.3 MPa (144 °C) and 0.6 MPa (165 °C) and for 120 s and 180 s. All treated samples were freeze-dried (Christ Alpha 1-2LD, Germany), sieved to pass 450 µm mesh size and kept at -18 °C for further analysis. The freeze-dried RB was manually crushed with a spatula instead of grinding before sieving to prevent any additional mechanical effect on the RB fibre properties.

Analysis of Physicochemical Properties of Rice Bran

Average Particle Size. The average particle size of RB fibres was determined by using scanning electron microscopy (SEM) images equipped with Nano Measure 1.2 Software (Fudan University, China) adapted from W. Wang et al. (2019) with a slight modification. The software was set up for the unit of particle size required (µm), and the counting of the particle size (based on the SEM images) and the average particle size of the sample were calculated automatically by the software. The measurements were done in triplicate.

Surface Microstructure. Examination of the microstructure of RB fibres before and after the ultrasound cavitation and steam explosion treatments was done using SEM according to the procedure described by Wen et al. (2017) with slight modifications. First, samples of RB fibre were placed and spread into a thin layer on a specimen holder with the help of double-sided scotch tape and sputter-coated with gold (5 min, 30 mm thickness). Finally, each sample was transferred to a microscope (SEM, Hitachi S3400, Japan), where it was observed at an accelerating voltage of 20 kV.

Bulk Density. The bulk density (BD) of RB fibres was analysed by Chau et al. (2007). The BD was recorded as a ratio of the weight (g) of the RB sample to its volume (mL).

Colour. The colour of the RB fibre before and after treatment was measured with a Minolta CR-400 Chromameter with a Xenon lamp as the light source (Konica, Japan) adapted from Kurek et al. (2017) with a minor modification. The L*, a*, and b* colour values were recorded by the instrument, with the L value (0–100) representing lightness on the surface, while a* and b* values representing the chromatic components of redness to greenness and blueness to yellowness that range from -120 to 120, respectively.

Water Binding Capacity. The extracted fibre's water binding capacity (WBC) was determined by the method described by Robertson et al. (2000) using an external centrifugal force with minimum modification. WBC was expressed as the amount of water retained per gram dry sample.

WBC (g/g) = (Residue hydrated weight after centrifugation - Residue dry weight) / Residue dry weight

Swelling Capacity. The swelling capacity (SC) of RB was analysed using the method of Robertson et al. (2000). The swelling capacity (SC) was expressed as mL per g of dry sample.

SC = Volume occupied by sample (mL) / Weight of the original sample (g)

Oil Binding Capacity. Oil binding capacity (OBC) was measured using a method adapted from Abdul-Hamid and Luan (2000). The oil binding capacity was expressed as absorbed oil per gram sample.

Statistical Analysis. The experiments were repeated twice, and all data were collected in triplicate. Data were analysed by one-way analysis of variance (ANOVA) to determine the significant differences, and Tukey pairwise comparisons were used to compare the significant difference between the treatments. The statistical analysis was performed using Minitab version 17 (USA).

RESULTS AND DISCUSSION

Average Particle Size

It has been reported that the drying of bran fibre can influence its particle size due to particle agglomeration that occurs during the drying process (Beck et al., 2012). Therefore, to consider the drying effect, the untreated unpurified RB was dispersed in the same amount of deionised water as ultrasound-treated samples and freeze-dried (FD). This sample is referred to as untreated FD (Table 1). The average particle size of unpurified untreated RB FD was 83.3 ± 10.1, which was not significantly ($p > 0.05$) different from the unpurified RB without freeze-drying, which was 78.274 ± 11.0 µm. Thus, it is worth noting that the changes in particle size of RB in this study were not due to the freeze-drying process.

Unpurified RB showed an increase in average particle size after treatment at 60% US amplitude as treatment time increased (Table 1). Meanwhile, after 80% US amplitude treatment, the average particle size only increased after 10- and 15-min treatments and then reduced with no significant ($p > 0.05$) difference with the untreated RB after 20 min treatment. For treatment at 95% amplitude, the average particle size continued to increase as the treatment time increased.

Purified RB without treatment had an average particle size of 188.9 ± 21.67 µm (Table 2). It was significantly ($p < 0.05$) bigger than the unpurified RB and showed that the purification process caused swelling of the particle as it had been soaked in water,

Table 1

The average particle size of unpurified RB after US treatment at different amplitudes and treatment times

US amplitude (%)	Treatment time (min)	Average particle size (µm)
0	0	[1]78.3 ± 11.0$^{A, c, y, Z}$
0	0	[2]83.3 ± 10.1$^{A,bc, y, Z}$
60	5	101.1 ± 5.9^{b}
	10	105.0 ± 3.3^{b}
	15	134.5 ± 3.4^{a}
	20	128.4 ± 11.0^{a}
80	5	83.2 ± 3.0^{y}
	10	115.0 ± 6.8^{x}
	15	114.3 ± 8.0^{x}
	20	84.8 ± 3.1^{y}
95	5	176.8 ± 4.8^{X}
	10	184.5 ± 9.9^{X}
	15	150.6 ± 8.2^{Y}
	20	174.3 ± 15.7^{X}

Note.
[1]Untreated defatted RB without being freeze-dried
[2]Untreated FD = Defatted RB and freeze-dried
^{A} = Means with different letters within the same column differ significantly ($p < 0.05$)
$^{a-c}$ = Means with different letters within the same column differ significantly ($p < 0.05$)
$^{x-y}$ = Means with different letters within the same column differ significantly ($p < 0.05$)
$^{X-Z}$ = Means with different letters within the same column differ significantly ($p < 0.05$)
Values of average particle size are means ± standard deviation (S.D.); $n = 3$

sodium hydroxide solution (NaOH) and undergone heat treatment during the process. After US treatment at all three amplitudes (60%, 80%, and 95%), the average particle size of purified RB decreased significantly ($p < 0.05$) compared to the untreated sample. However, no significant ($p < 0.05$) differences were observed between the 60% and 80% US amplitudes treatment times. At 95% US amplitude for treatment, the changes in average particle size fluctuated over the treatment time. However, all of them were still smaller than the untreated RB. This finding was in agreement with the previous studies by Hu et al. (2015) and Sumari et al. (2013). They observed similar effects of US treatment on the particle size of purified wheat bran and cellulose.

The average particle of unpurified RB after SE treatment was increased compared to untreated RB (Table 3). In contrast, the SE treatment decreased particle size for purified bran, similar to the effect of US treatment on purified bran. However, there were no significant ($p < 0.05$) differences between the particle sizes when the steam pressure was increased from 0.3 MPa to 0.6 MPa for both unpurified and purified RB.

Both US and SE are severe physical treatments that can significantly alter the particle size of RB. US produce a large number of microbubbles through acoustic cavitation, which, when collapsed, generate a high intensity of local energy (Hromádková et al., 2002; Sumari et al., 2013), thus degrading the particles of the material into smaller sizes. It was reflected in the reduction of particle size of the purified RB when treated by the US. However, the decrease in the particle size of the RB did not correlate with the US intensity. Furthermore, longer treatment times for the same US amplitude did not lead to a further reduction in the particle size. In contrast, higher US amplitude resulted in a smaller reduction in the particle size. These results appear to suggest a limit regarding

the effect of US treatment on the particle size of purified RB. If the treatment intensity was too high, agglomeration could occur. Meanwhile, the reduction in particle size after SE treatment of purified RB was due to the sudden release of the high pressure applied, which would shatter the bran particles into smaller pieces. To the best of our knowledge, no study has reported the effect of SE on the particle size of cereal bran. However, Yu et al. (2014) observed the reduction of particle size of taro pulp after high-pressure homogeniser treatment, which broadly agrees with our findings.

On the other hand, the increases in the particle size of unpurified RB by both US and SE treatments were most likely due to starch and protein, which swelled when dispersed in the water. In addition, the size of starch granules increased after high-pressure treatment due to starch gelatinisation (B. Wang et al., 2008; W. Wang et al., 2016).

Table 2

The average particle size of purified RB after US treatment at different amplitudes and treatment times

US amplitude (%)	Treatment time (min)	Average particle size (μm)
0	0	$188.9 \pm 21.7^{A, a, x}$
60	5	88.1 ± 1.5^{B}
	10	98.3 ± 17.7^{B}
	15	80.0 ± 6.3^{B}
	20	87.2 ± 6.3^{B}
80	5	102.2 ± 15.9^{b}
	10	126.3 ± 18.2^{b}
	15	120.6 ± 14.9^{b}
	20	131.4 ± 17.7^{b}
95	5	112.1 ± 0.9^{z}
	10	153.9 ± 9.1^{y}
	15	119.9 ± 5.4^{z}
	20	148.9 ± 7.8^{y}

Note.

$^{A-B}$ = Means with different letters within the same column differ significantly ($p < 0.05$)

$^{a-c}$ = Means with different letters within the same column differ significantly ($p < 0.05$)

$^{x-z}$ = Means with different letters within the same column differ significantly ($p < 0.05$)

Values of average particle size are means ± standard deviation (S.D.); $n = 3$

Table 3

The average particle size of unpurified and purified RB after SE treatment

Rice bran	Pressure (MPa)	Treatment time (min)	Average particle size (μm)
Unpurified	0	0	$^{1}78.3 \pm 11.0^{A,b}$
	0	0	$^{2}83.3 \pm 10.1^{A,b}$
	0.3	2	216.8 ± 5.9^{a}
	0.6	2	221.7 ± 17.1^{a}
Purified	0	0	$188.9 \pm 21.7^{a'}$
	0.3	2	$120.8 \pm 18.6^{b'}$
	0.6	2	$141.4 \pm 29.8^{a'b'}$

Note.

[1]Untreated defatted RB without freeze-dried

[2]Untreated FD = Defatted RB and freeze-dried

$^{A-B}$ = Means with different letters within the same column differ significantly ($p < 0.05$)

$^{a-b}$ = Means with different letters within the same column differ significantly ($p < 0.05$)

$^{a'-b'}$ = Means with different letters within the same column differ significantly ($p < 0.05$)

Values of average particle size are means ± standard deviation (S.D.); $n = 3$

Changes in the Surface Microstructure

The surface microstructure of unpurified and untreated RB (original) showed a packed, hard, and granular shape (Figure 1 A). Meanwhile, small shrinkages were observed on the untreated FD sample, but the porosity of the RB showed no changes (Figure 1 B). This finding is partly in agreement with the results reported by Y. Liu et al. (2017), who also observed shrinkage of the soluble fraction but, at the same time, found the formation of the porous structure on the insoluble fraction of orange peel fibre after freeze-drying. The difference was likely due to the different types of dietary fibre used in the two studies, and heat treatments were given to the fibre.

After the US treatment, the surface microstructure of unpurified RB became porous, broken into smaller pieces, flaky, and flat-shaped, and this effect became more apparent when the US amplitude and time were increased from 60% to 95% and 5 to 20 min, respectively (Figure 1 C - N). A similar disruption in the structure of chestnut polysaccharides after US treatment was observed in previous studies (Hou et al., 2016; Ying et al., 2011).

In contrast, SE treatment did not give an impact as significant as the US on the surface structure of RB. There were no changes in the surface structure of RB when treated at 0.3 MPa for 2 min. However, a small change in porosity was observed when treated at the higher pressure of 0.6 MPa for the same length of time, as shown in Figure 1 O-P. This result is in disagreement with the finding observed in wheat bran (Jiang & Guo, 2016). However, the parent reason for the different effects observed was not clear and could be due to the different types of fibre used in their studies, which had different cell wall strengths. Furthermore, Jiang and Guo (2016) applied higher pressures (up to 3.7 MPa) in their study, which was much higher than the pressure used in this study. Therefore, the relatively low steam pressure used in this study might not be enough to cause significant changes to the surface structure of RB.

It is found that some shrinkage and small holes occurred in the structure of untreated RB after the purification (Figure 2 A). It could be due to the soaking and high temperature applied during the purification process. After the US treatment, the same effect as the unpurified RB was observed, where the porosity increased as the US amplitude and time increased (Figure 2 B - M). Moreover, similar to the effect observed with unpurified bran, the purified bran treated by SE did not show noticeable changes in the microstructure (Figure 2 N - O). It again can be related to the lower pressures used in this study compared to the previous study by Jiang and Guo (2016), who applied higher pressure on wheat bran (1.0 - 3.7 MPa).

Bulk Density

For unpurified RB, with treatments at 60% and 80% US amplitudes, at all US times, the BD decreased by about 50%–60% (data not shown) from the untreated RB. However, no significant ($p > 0.05$) difference between these two amplitudes

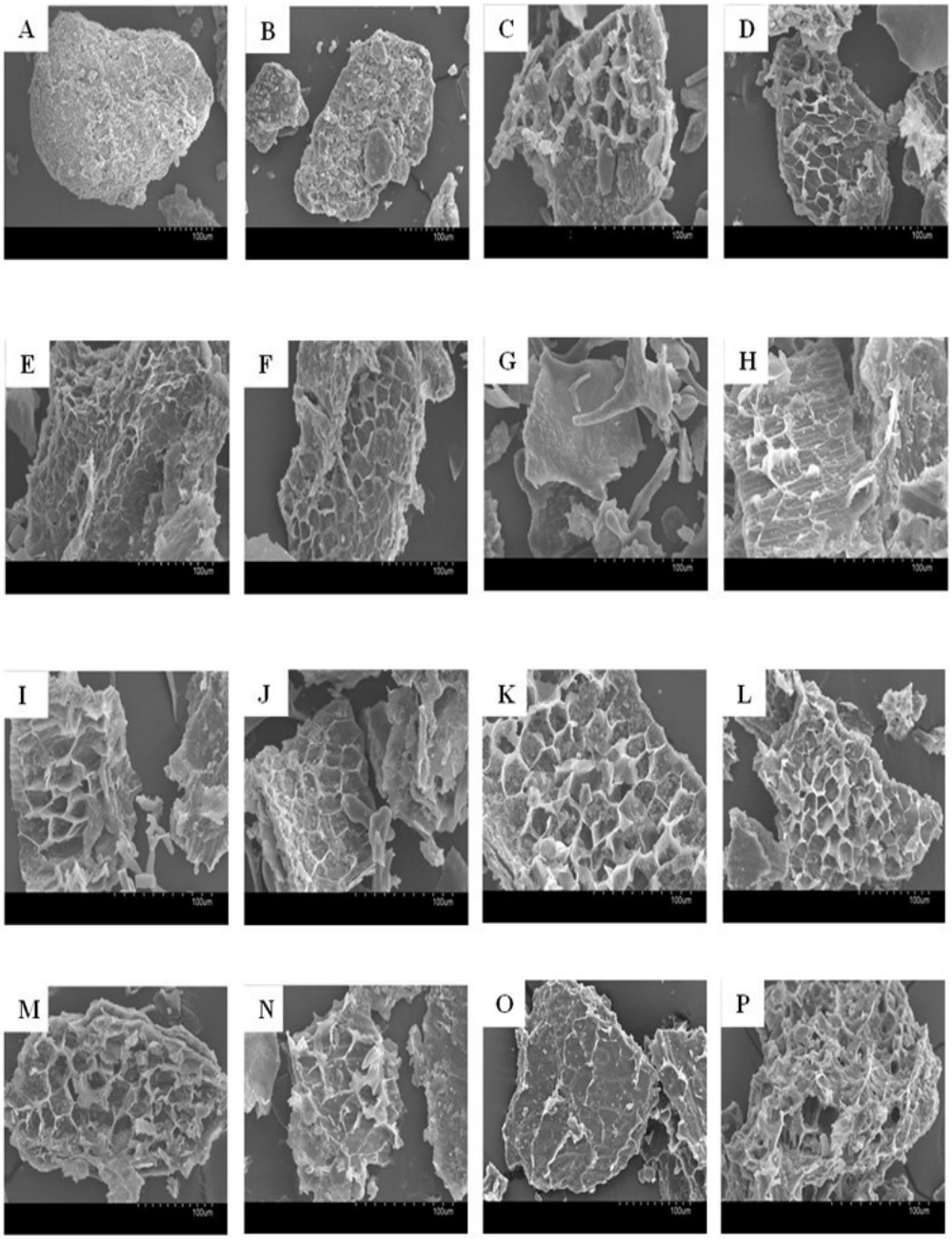

Figure 1. SEM images of un-purified RB fibre after ultrasound and steam explosion treatment

Note. A = Untreated; B = Untreated freeze-dried (untreated FD); C = Ultrasound at 60% amplitude for 5 min (same for the following); D = 60%, 10 min; E = 60%, 15 min; F = 60%, 20 min; G = 80%, 5 min; H = 80%, 10 min; I = 80%, 15 min; J = 80%, 20 min; K = 95%, 5 min; L = 95%, 10 min; M = 95%, 15 min; N = 95%, 20 min; O = Steam explosion at 0.3MPa, 2 min; P = Steam explosion at 0.6MPa, 2 min

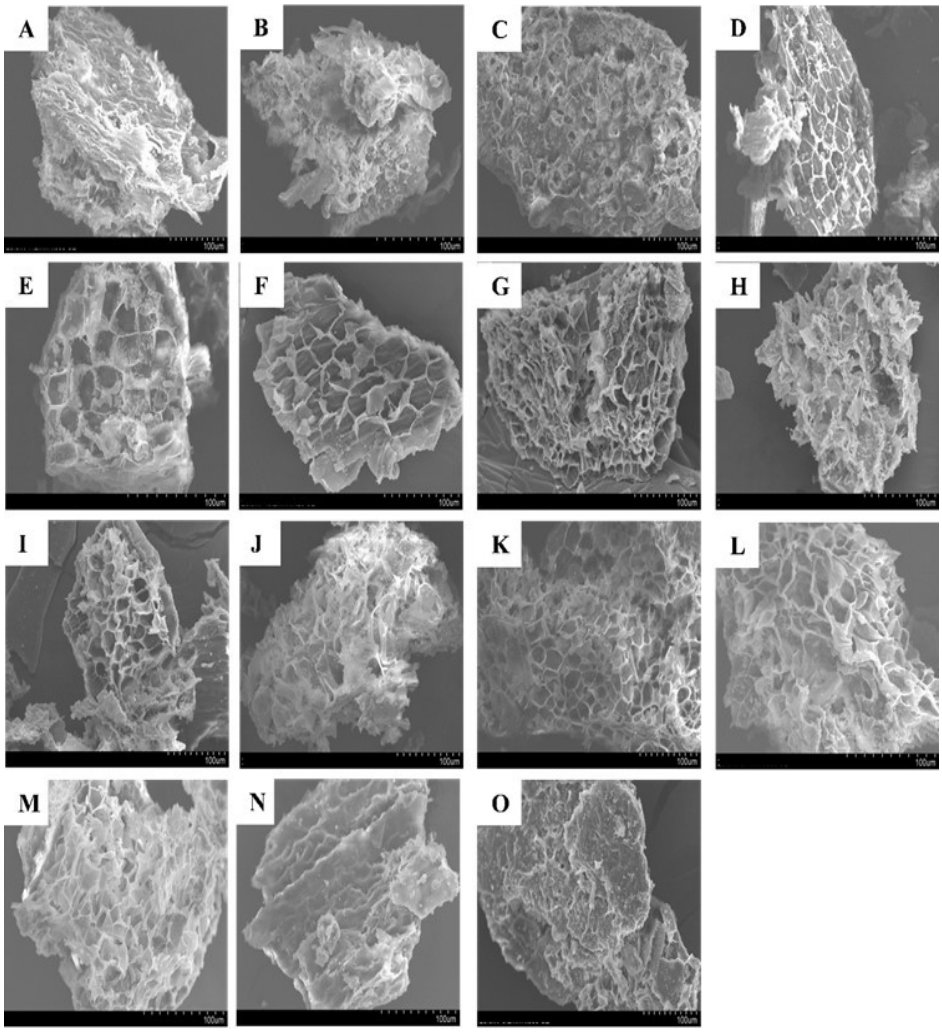

Figure 2. SEM images of purified RB fibre after ultrasound and steam explosion treatment

Note. A = Untreated; B = Ultrasound treated 60% amplitude for 5 min (same for the following); C = 60%, 10 min; D = 60%, 15 min; E = 60%, 20 min; F = 80%, 5 min; G = 80%, 10 min; H = 80%, 15 min; I = 80%, 20 min; J = 95%, 5 min; K = 95%, 10 min; L = 95%, 15 min; M = 95%, 20min; N = 0.3MPa, 2min; O = 0.6MPa 2 min

was observed. However, when the US amplitude was increased to the maximum (95%), the reduction of the BD was less than at the previous two amplitudes, at around 42%–48% (data not shown). Nevertheless, no significant differences ($p > 0.05$) in the BD at all US amplitude were observed when US treatment time was increased from 5 to 20 min.

After purification, the BD of untreated RB was reduced by about 45% compared with the unpurified bran, from 0.53 g/mL to 0.23 g/mL. The bulk density of purified RB steeply decreased with increment of US

amplitude and time of treatment (Figure 3B). However, no significant ($p > 0.05$) differences were observed between 60% and 80% amplitudes at all treatment times. The lowest BD was recorded (0.15 g/mL) with treatment at 95% for 20 min.

SE treated unpurified RB also showed a decrement of BD, but no significant ($p > 0.05$) difference was observed when the pressure was increased from 0.3 MPa to 0.6 MPa. The SE treatment only reduced the BD of unpurified RB by 20.5% compared to untreated RB (Figure 3C). In contrast, treatment of purified RB with the SE at 0.3 MPa and 0.6 MPa caused an increase in the BD by 17.9% (at both pressures) compared to the untreated RB.

Bulk density is a physical property that can be influenced by many factors, such as the porosity and size of particles as well as the processing methods used (Z. Liu et al., 2016). The lower bulk density of the purified RB compared to the unpurified counterpart indicated that the purification process had altered the structure of the bran by making it more porous, which is reflected in the SEM results (Figure 2A). It is expected as the removal of starch and protein from the bran would leave some space in the bran structure. Therefore, it is generally expected that bran with a more porous structure would have a lower BD. Moreover, a reduction in particle size would also lead to lower BD, as shown by many studies (Chau et al., 2007; Huang et al., 2010; T. Wang et al., 2012; Wang, Raddatz, et al., 2013). In this study, the porosity of RB decreased with the intensity of US treatment (as shown in section "Changes in the Surface Microstructure"). At the same time, its effect on the reduction in particle size was inconsistent and did not show a clear pattern. However, in the case of SE, the treatment caused an increase in particle size. Nevertheless, all treatments caused a reduction in the bulk density of the RB. In the case of US treatment, the reduction was more pronounced with increasing treatment intensity. These results demonstrated that the influence of porosity on the BD of RB fibre was greater than the particle size.

Moreover, BD has reportedly been influenced by drying methods such as oven drying or freeze-drying (Y. Liu et al., 2017). Therefore, the bulk density of freeze-dried untreated unpurified RB (untreated FD) was analysed to remove the possibility that the reduction in BD is an effect of drying. The BD of untreated FD was 0.374 g/mL (not shown in the graph), which was 29% ($p < 0.05$) lower than untreated RB that had not been freeze-dried. The bulk density of US-treated RB at all US amplitudes was significantly ($p < 0.05$) lower than the untreated FD. At amplitudes 60%, 80%, and 95%, the reduction of the bulk density was 39-45%, 30-41%, and 17-27% compared to untreated FD, respectively (data not shown). According to Y. Liu et al. (2017), freeze-drying led to the formation of a porous structure in dietary fibre, which would cause a decrease in its BD. However, in this study, the freeze-drying process did not significantly alter the porosity of untreated RB (Figure 1 B). Therefore, it indicates that the reduction in the bulk US treated RB

was not due to the freeze-drying process applied after the treatment; indeed, it was attributable to the increase in porosity and reduction in the particle size of the RB as a result of the treatment.

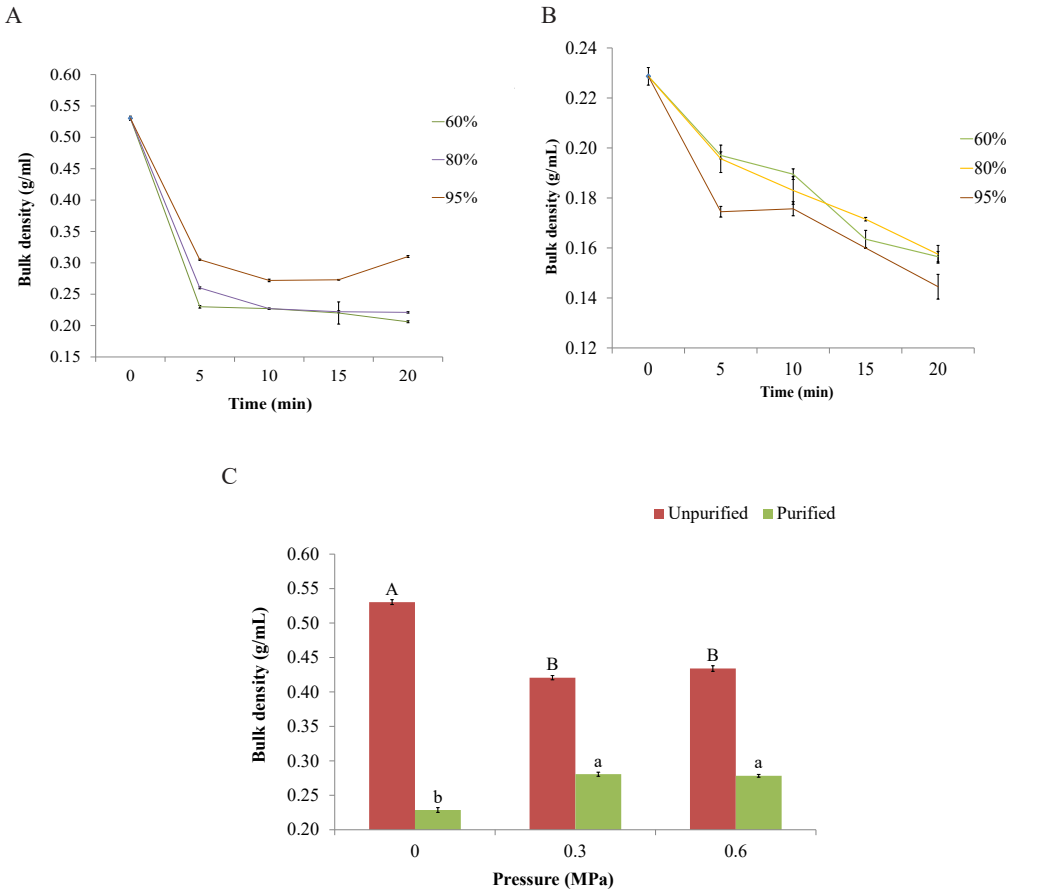

Figure 3. Bulk density

A) Bulk density of unpurified RB after ultrasound treatment
B) Bulk density of purified RB after ultrasound treatment
C) Bulk density of unpurified and purified rice bran after steam explosion treatment

Note.
A-B = Means with different letters are differ significantly ($p < 0.05$)
a-b = Means with different letters are differ significantly ($p < 0.05$)
Values are means ± standard deviation (S.D.). $n = 3$

Colour Changes

A decrease in lightness (L* value) of unpurified RB was observed after US treatment at all amplitudes applied, and the decrease became greater as the US amplitude increased (Table 4). Furthermore,

the darkest colour of the bran was observed with the highest US amplitude (95%) and the longest time of treatment (20 min). Meanwhile, US treatment caused the a* value of the bran to increase, but the b* value did not change significantly ($p > 0.05$) after the treatment.

Purified RB had a lower L* value than the unpurified bran, likely attributable to the high temperature used during the gelatinisation steps to remove starch. After US treatment, a further decrease in L* values occurred. However, the L* values did not decrease as low as that observed in unpurified RB. Besides, the a* value also decreased as the US amplitude and time increased, with the lowest value observed at 95% amplitude and 20 min. In contrast, the b* value showed an increase compared to the untreated RB.

The colour of unpurified RB became darker after SE treatment compared to untreated and US-treated RB, which is evident by the lower L* values (Table 5). Furthermore, the L, a*, and b* values decreased as the steam pressure increased from 0.3 MPa and 0.6 MPa.

The colour values changes (L*, a*, b*) in RB after the US and SE treatment were mainly due to the Maillard reaction and sugars caramelisation generated by the starch and polysaccharides breakdown in the RB (Rosell, 2011). Although US is a nonthermal treatment, small rises in temperature of the bran were observed during the treatment, which became more pronounced with time, which would expect to accelerate the browning reaction. Severe browning was expected with the SE treatment due to the high temperatures involved, which was reflected in the large increases of the a* (redness) and b* (yellowness) values. When the purification process removed the starch and protein, which are key participants or precursors of Maillard browning and caramelisation, the magnitudes of darkening changes were much less, which were reflected in the lesser decreases of L* (lightness) values for purified RB.

Table 4

Colour values of RB after US treatment

	US amplitude (%)	Treatment time (min)	Colour value		
			L*	a*	b*
Unpurified bran	0	0	$70.2 \pm 0.2^{A, a, v}$	$3.6 \pm 0.1^{C, b, v}$	$17.5 \pm 0.2^{A, b, w}$
	60	5	66.4 ± 1.0^{B}	4.0 ± 0.1^{A}	17.7 ± 0.3^{A}
		10	66.4 ± 0.6^{B}	4.1 ± 0.1^{A}	17.5 ± 0.3^{A}
		15	66.6 ± 0.2^{B}	3.6 ± 0.1^{C}	17.9 ± 0.2^{A}
		20	67.3 ± 0.0^{B}	3.8 ± 0.1^{B}	17.8 ± 0.0^{A}

Table 4 *(Continue)*

	US amplitude (%)	Treatment time (min)	Colour value		
			L*	a*	b*
	80	5	67.1 ± 0.1^{c}	4.3 ± 0.1^{a}	18.4 ± 0.1^{a}
		10	67.1 ± 0.4^{c}	3.8 ± 0.1^{a}	17.6 ± 0.1^{b}
		15	68.4 ± 1.4^{b}	3.6 ± 0.0^{b}	17.3 ± 0.1^{b}
		20	69.6 ± 1.3^{a}	3.6 ± 0.1^{b}	17.7 ± 0.2^{b}
	95	5	67.9 ± 0.1^{w}	3.8 ± 0.0^{w}	17.8 ± 0.0^{vw}
		10	67.4 ± 0.1^{x}	3.7 ± 0.0^{w}	17.7 ± 0.0^{vw}
		15	65.4 ± 0.5^{y}	3.9 ± 0.0^{w}	17.9 ± 0.0^{v}
		20	65.1 ± 0.1^{z}	3.9 ± 0.0^{w}	17.5 ± 0.0^{vw}
	0	0	$68.4 \pm 0.2^{A, a, x}$	$4.2 \pm 0.0^{A, a, v}$	$19.2 \pm 0.0^{D, d, v}$
	60	5	68.3 ± 0.1^{B}	3.4 ± 0.1^{B}	21.3 ± 0.0^{B}
		10	68.7 ± 0.7^{B}	3.4 ± 0.1^{B}	21.7 ± 0.1^{A}
		15	69.4 ± 0.1^{B}	3.5 ± 0.0^{B}	21.8 ± 0.1^{A}
		20	70.6 ± 0.7^{B}	3.2 ± 0.1^{C}	20.7 ± 0.1^{C}
Purified bran	80	5	66.9 ± 0.1^{b}	3.5 ± 0.0^{b}	20.1 ± 0.0^{c}
		10	66.9 ± 0.0^{b}	3.4 ± 0.2^{c}	20.2 ± 0.0^{c}
		15	66.6 ± 0.2^{b}	3.4 ± 0.0^{c}	20.8 ± 0.0^{a}
		20	65.5 ± 0.1^{c}	3.3 ± 0.1^{c}	20.6 ± 0.1^{b}
	95	5	67.3 ± 0.0^{x}	3.3 ± 0.1^{w}	20.6 ± 0.2^{w}
		10	67.2 ± 0.1^{x}	3.3 ± 0.0^{w}	20.8 ± 0.2^{w}
		15	67.7 ± 0.5^{x}	3.3 ± 0.1^{w}	21.4 ± 0.3^{w}
		20	67.7 ± 0.1^{x}	3.0 ± 0.0^{x}	20.5 ± 0.2^{w}

Note.
Values within the same column with different letters were significantly different ($p < 0.05$) Values are means ± standard deviation (S.D.). $n = 3$
The means values were compared with the untreated (0 amplitude and 0 times) as a control for unpurified and purified, respectively
$^{A-D}$ = Means with different letters within the same column and the same US amplitude differ significantly ($p < 0.05$)
$^{a-d}$ = Means with different letters within the same column and the same US amplitude differ significantly ($p < 0.05$)
$^{v-z}$ = Means with different letters within the same column and the same US amplitude differ significantly ($p < 0.05$)

Table 5

Colour values of RB after SE treatment

	Pressure (MPa)	Treatment time (min)	Colour value		
			L	a*	b*
Unpurified bran	0.0	0	70.2 ± 0.2^{A}	3.6 ± 0.1^{C}	17.5 ± 0.2^{A}
	0.3	2	55.8 ± 0.1^{B}	5.9 ± 0.1^{B}	16.3 ± 0.3^{B}
	0.6	2	51.4 ± 0.1^{C}	6.6 ± 0.1^{A}	16.3 ± 0.1^{B}
Purified bran	0.0	0	68.4 ± 0.2^{a}	4.2 ± 0.0^{e}	19.2 ± 0.0^{b}
	0.3	2	65.6 ± 0.6^{b}	4.6 ± 0.2^{b}	19.3 ± 0.4^{b}
	0.6	2	62.6 ± 0.5^{c}	5.1 ± 0.2^{a}	20.2 ± 0.9^{a}

Note.

Values within the same column with different letters were significantly different ($p < 0.05$)

The means values were compared with the untreated (0 amplitude and 0 times) as a control for unpurified and purified, respectively

$^{A-C}$ = Means with different letters within the same column differ significantly ($p < 0.05$)

$^{a-c}$ = Means with different letters within the same column differ significantly ($p < 0.05$)

Values are means ± standard deviation (S.D.). *n = 3*

Water Binding Capacity

Water Binding Capacity (WBC) of unpurified RB did not show a clear trend over the amplitude and time of US treatment (Figure 4A). The WBC of unpurified and purified RB before physical treatment was 3.1 and 6.3 g/g, respectively, showing that the purification process increased the WBC of RB by two folds. The purified RB showed a clear trend in the relationship between water binding capacity and the severity of US treatment, where an increase in treatment amplitude and time generally led to an increase in the water-binding capacity of the bran samples (Figure 4B). At 60% US amplitude, there was no significant ($p > 0.05$) effect on the WBC of purified RB fibres after 5, 10, and 15 min of treatment, but the WBC increased steeply to 7.9 g/g after 20 min of treatment and gave the highest WBC value. At the maximum amplitude (95%), the WBC ($p < 0.05$) increased significantly from 6.4 to 6.90 g/g after 5- and 10-min treatment, respectively, but no further significant increment was observed when the US time was increased to 15 and 20 min. It was also observed that there was no significant ($p < 0.05$) difference between WBC at 80% and 95% US amplitudes for 10 and 15 min of treatment.

In contrast, the WBC of both unpurified and purified RB decreased after SE treatment (Figure 4C). The WBC of unpurified RB before treatment was 3.1 g/g, reduced to 2.2 g/g and 2.4 g/g after being treated with the SE at 0.3 MPa and 0.6 MPa for 2 min,

respectively. For purified RB, the WBC was reduced to 3.3 g/g and 3.5 g/g. No significant ($p > 0.05$) difference was observed between the WBC of RB treated by the SE at the two different pressure levels.

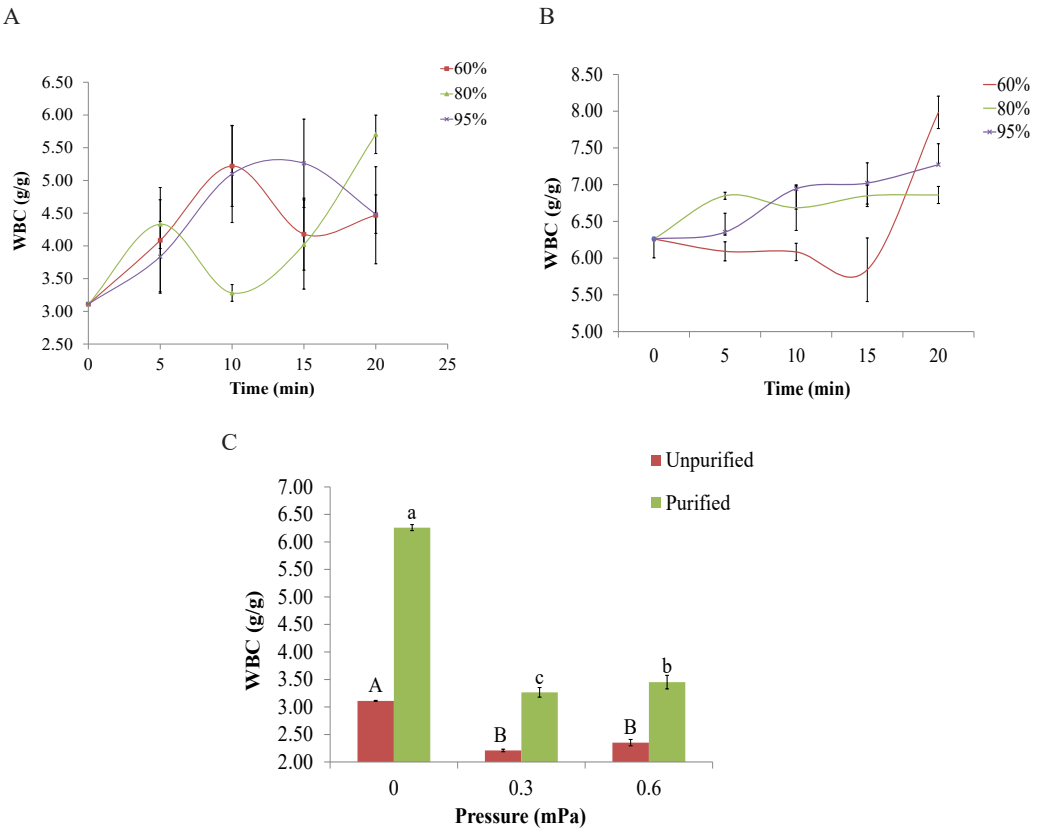

Figure 4. Water binding capacity
A) Water binding capacity of unpurified rice bran after ultrasound treatment
B) Water binding capacity of purified rice bran after ultrasound treatment
C) Water binding capacity of unpurified and purified rice bran after steam explosion treatment

Note.
A-B = Means with different letters differ significantly ($p < 0.05$)
a-b = Means with different letters differ significantly ($p < 0.05$)
Values are means ± standard deviation (S.D.). $n = 3$

Swelling Capacity

Swelling capacity (SC) showed significant ($p < 0.05$) changes after the US treatment. At each amplitude, the SC of the RB increased with treatment time, reached a plateau, and then declined (Figure 5A). Surprisingly, US at 60% amplitude for 5 min resulted in the highest SC value for the unpurified

bran, which declined with further increased treatment time. The SC of bran treated at 80% and 95% amplitudes reached a peak at 20 and 5 min, respectively, and then declined.

Purification of RB caused its swelling capacity to increase by about 22% before physical treatment (Figure 5B). It is likely because the removal of starch and protein left more binding sites for water uptake (Qi et al., 2015, 2016). Furthermore, purification also made the RB more responsive to US treatment. At 60% US amplitude, the SC increased to 8.7, 9.2, and 9.2 mL/g after 5, 10, and 15 min of treatment, respectively. However, after 20 min of US treatment, the SC increased to the highest value compared to US treatment at 80% and 95% amplitudes. This trend was in agreement with the WBC results, where the highest WBC value was also observed at 60% US amplitude and 20 min, as described in the proceeding section. However, slightly different trends were observed at 80% and 95% amplitudes. At 80% US amplitude, the SC increased after 5 min of treatment, remained largely constant between 5 and 15 min, and increased again after that. Meanwhile, at 95% US amplitude, the SC increased as the time increased. Overall, the swelling capacity of purified RB was significantly ($p < 0.05$) higher after the US treatment.

For SE treatment, the SC of unpurified and purified RB decreased after the treatment, as shown in Figure 5C, similar to the results for WBC as described in the previous section. For the unpurified bran sample, the SC decreased from 5.7 g/g (untreated) to 4.9 g/g and 4.7 g/g after being treated at 0.3 MPa and 0.6 MPa, respectively. For the purified RB, the SC decreased from 7.3 g/g to 6.4 g/g and 6.5 g/g after treatment at the same pressure. However, the SC values did not differ significantly ($p > 0.05$) between treatments at the two pressures for both unpurified and purified RB.

Oil Binding Capacity

The oil binding capacity (OBC) of untreated unpurified RB was 1.8 g/g. After 5 min of US treatment with different US amplitudes, the OBC significantly increased. With US applied at 60% and 80% amplitudes, the OBC showed no further significant changes ($p > 0.05$) when the treatment time was increased. However, with 95% US amplitude, the OBC increased continuously with increasing treatment time (Figure 6A).

The OBC of untreated RB increased to 4.1 g/g after purification (Figure 6B). Regarding the effect of US treatment on the OBC of purified RB, a different trend was observed from that of unpurified bran. After 5 min of US treatment at 60% and 95% amplitudes, no significant differences ($p > 0.05$) were observed in OBC compared to the untreated sample. At 60% amplitude, significant increases in OBC only occurred with a further increase in treatment time after 5 min, and the OBC increased sharply as the time increased from 5 to 20 min. At 95% amplitude, the maximum OBC was observed after 10 min of treatment and no further changes occurred as the treatment time increased. At 80% amplitude, the OBC

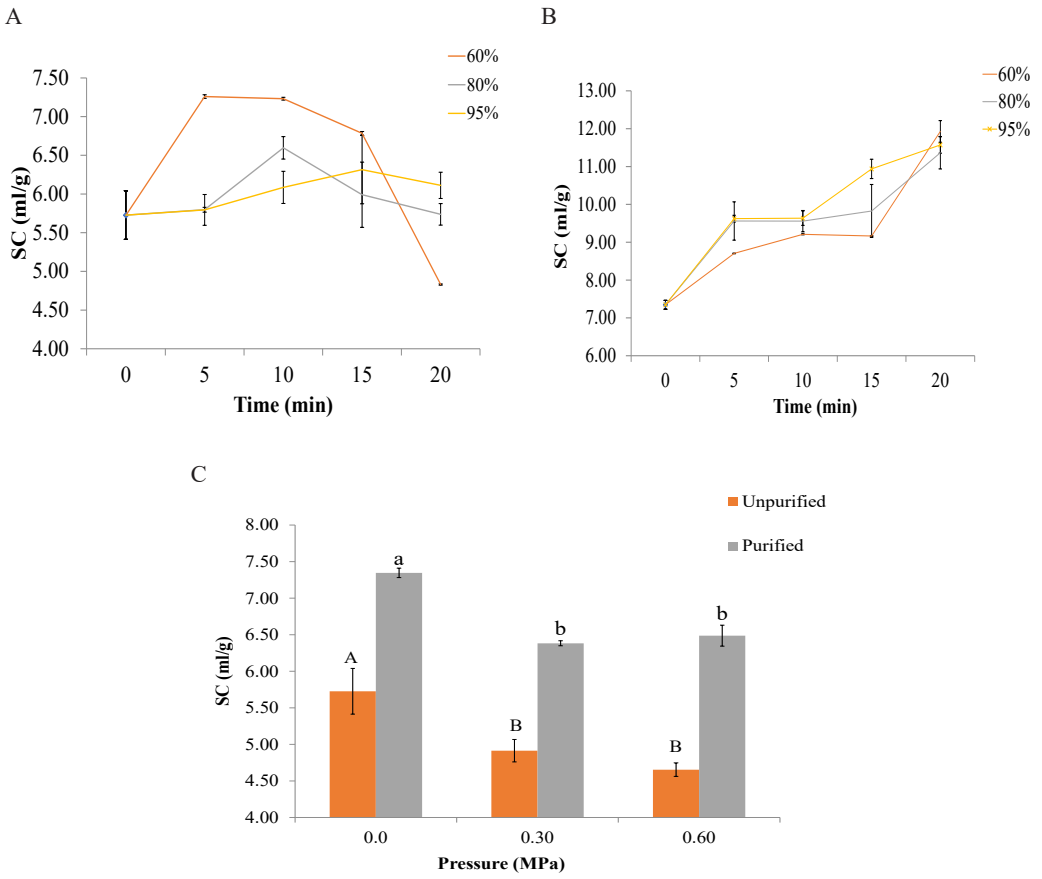

Figure 5. Swelling capacity
A) Swelling capacity of unpurified rice bran after ultrasound treatment
B) Swelling capacity of purified rice bran after ultrasound treatment
C) Swelling capacity of unpurified and purified rice bran after steam explosion

Note.
A-B = Means with different letters differ significantly ($p < 0.05$)
a-b = Means with different letters differ significantly ($p < 0.05$)
Values are means ± standard deviation (S.D.). $n = 3$

increased sharply after 5 min of treatment and no significant changes ($p > 0.05$) were observed with further increase in treatment time. The highest OBC was observed at 60% US amplitude and 20 min of treatment.

The OBC of SE-treated RB is shown in Figure 6C. Treatment with SE resulted in a significant decrease in the OBC of purified RB, and the reduction was greater at 0.6 MPa than at 0.3 MPa. However, for unpurified RB, the SE treatment showed no significant ($p > 0.05$) effect on OBC.

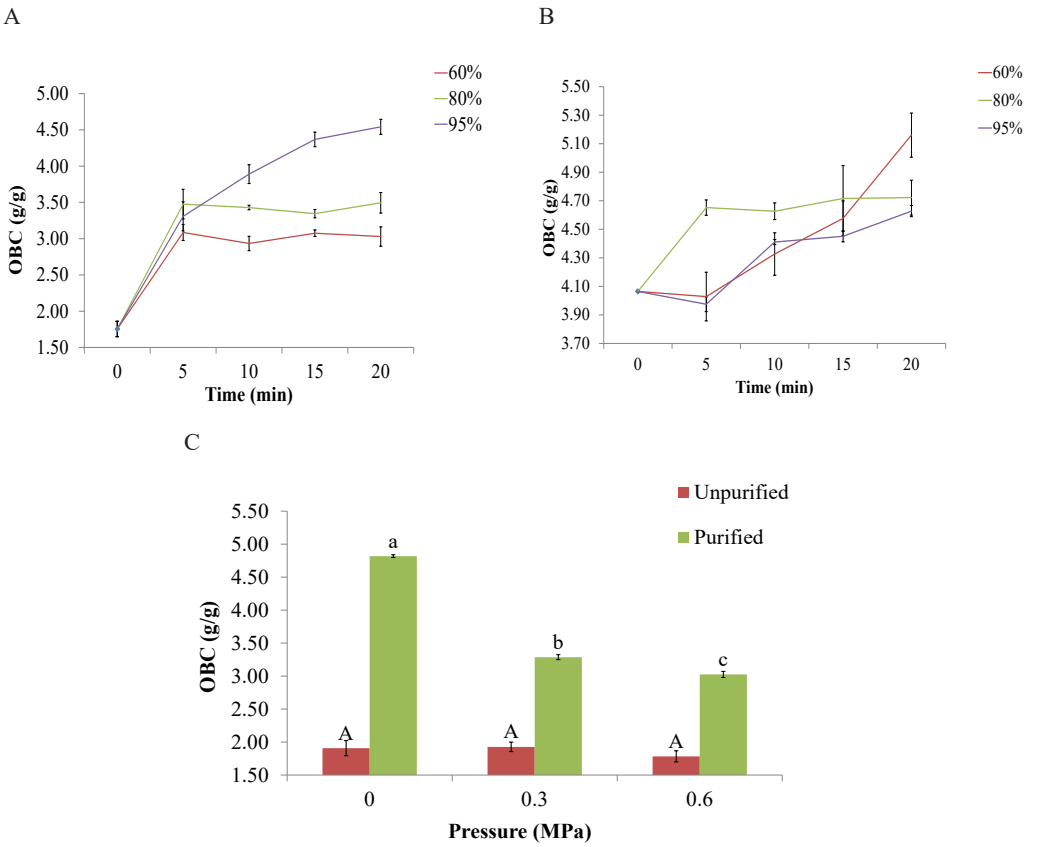

Figure 6. Oil binding capacity
A) Oil binding capacity of unpurified rice bran after ultrasound treatment
B) Oil binding capacity of purified rice bran after ultrasound treatment
C) Oil binding capacity of unpurified and purified rice bran after steam explosion treatment

Note.
A-B = Means with different letters differ significantly ($p < 0.05$)
a-b = Means with different letters differ significantly ($p < 0.05$)
Values are means ± standard deviation (S.D.). $n = 3$

General Discussion on the Changes in the Physicochemical Properties of RB After US and SE Treatment

Water-binding capacity (WBC) and swelling capacity (SC) are important hydration properties of fibres as they perform important functions in food products as well as in human physiology (Blackwood et al., 2000; Chater et al., 2015; Rosell, 2011; Rosell & Santos, 2010; Sabanis et al., 2009). The ability of dietary fibre to retain water is strongly influenced by the chemical and structural properties of the fibre (Chaplin, 2003). The inconsistent trend of water binding capacity observed in unpurified RB after US treatment was likely due to the presence of starch and protein. Purifying RB by removing starch and protein significantly

increased the water-binding capacity even before physical treatment was applied. It is expected as the removal of impurities, such as starch and protein from dietary fibre would increase the porosity (as shown in Figure 2A), surface area and expose more hydroxyl and carboxyl groups and capillary spaces between the cell wall structures of dietary fibre, which would increase the water-binding capability (Qi et al., 2015, 2016).

The effect of US treatment on the WBC and SC of purified RB was rather complex and not straightforward. At lower US amplitudes, longer treatment times were needed to produce a significant effect on WBC and SC, but it could achieve a greater increase in WBC and SC with prolonged treatment. On the other hand, high US amplitudes could increase the WBC for a shorter treatment time, but the prolonged treatment did not make further gains in WBC. These results were likely attributable to the effect of US treatment on the physical and chemical properties of RB. Initially, an increase in US treatment intensity (amplitude and time) would cause an increase in the porosity of the fibre matrix, with consequent increases in WBC and SC. However, as the US intensity was increased further, the porosity of the fibre matrix might not increase further as the structure had been opened to its limit (as shown in Figure 5), and all possible binding sites were occupied by water. Our results agreed with the findings of Ulbrich and Flöter (2014), who observed insignificant increments in cellulose-based oat fibre product WBC, even long cycles of high-pressure homogenisation treatment were applied as the maximum level of porosity was achieved. High-intensity US treatment could also result in cleavage of glycosidic bonds in the main polymeric chain as well as in the branching units, with consequent loss of sugars from the fibre (Ebringerová & Hromádková, 2010). The breakdown of the main polymer chain and side chains means a loss of hydrogen bonding sites, which could reduce the fibre's ability to retain water, which explains the lower WBC of RB when treated at higher US amplitude and longer treatment times.

WBC and SC are also related to the particle size of the fibre. In separate studies, Stephen and Cummings (1979) and Wang, Sun, et al. (2013) reported that the reduction in the particle size of wheat and corn bran by grinding leads to increases in WBC and SC as more surface area became available for water binding and absorption. It is in broad agreement with our findings where the WBC and SC of purified RB treated by US increased, corresponding to a reduction of the bran particle size (Table 2). However, a contradicting effect was reported on ground ash gourd and radish fibres, where the decrease in fibre particle size resulted in increased WBC (Gupta & Premavalli, 2010). The difference might be due to the different chemical compositions of the different fibres studied (Gupta & Premavalli, 2010; Raghavendra et al., 2006). The WBC of purified and US-treated RB in this study was lower than the WBC of RB that was treated with sulphuric acid (10–22.45 g/g)

(Qi et al., 2015). It suggests that methods of fibre preparation can also impact the WBC of RB. However, for unpurified and US-treated RB, it is difficult to relate the particle size to the WBC and SC as they fluctuate due to the interference of starch and protein, as discussed already. The reduction in WBC and SC of RB after SE treatment was likely linked to the morphological changes, where the surface structure of SE treated RB became packed, shrunk, and less porous compared to untreated and US treated RB, as shown in Figure 1 O - P and Figure 2 N - O.

In summary, US treatment resulted in increases in the WBC of RB, and it could be valuable for application in food products to prevent syneresis, modify viscosity, texture, and mouthfeel characteristics, as well as reduce calories of formulated food products (Chau et al., 2006). Besides, the WBC of fibre has been demonstrated to play an important role in bakery products as it influences major events that occur during baking, such as starch gelatinisation, protein denaturation, gluten dilution, and formation of flavour and colour (Rosell, 2011; Rosell et al., 2010). In addition, water binding also retards moisture loss during the storage of baked goods, which helps slow down the staling process of the products, especially bread (Ranasalva & Visvanathan, 2014; Sabanis et al., 2009; Walter, 2014). In terms of physiological properties, the ability of dietary fibre to entrap water is closely related to the digestion process, such as gastric emptying, faecal bulk, and gut transit time (Chater et al., 2015; Davidson & McDonald, 1998; Takahashi et al., 2009). A greater SC is also a desirable physicochemical property to be included as a food ingredient as it can induce satiety and improve bowel movement (Kuan & Liong, 2008). The WBC of dietary fibre also may affect nutrient absorption, postprandial satiety, and intestinal motility (Jenkins et al., 1978).

Similar to hydration properties, oil binding capacity is also influenced by several factors, including surface structure, particle size, overall charge density, and hydrophobicity of the components. Wang, Sun, et al. (2013) concluded that increased porosity led to more surface exposure and enhancement of the physical entrapment of oil by capillary attraction. Our results generally support it (Figure 1 C - N, Figure 2 B - M). Besides the porosity, the increase in OBC of purified and US-treated RB could also be attributed to the reduction in the average particle size. These findings are in agreement with the report by Chen et al. (2013), who studied the effect of particle size reduction on the OBC of oat bran and peach and found that the OBC was improved after US treatment. Although the OBC of US-treated RB in this study was lower than the OBC of chemically treated RB reported by Qi et al. (2015), the improvement by the treatment was nevertheless significant and had practical value. According to a previous study, rice bran fibre with high oil binding capacity are desirable as it has the potential for use in products such as gluten-free bread, pasta, and meat products to prevent agglomeration, alter the food matrix and stabilise high-fat foods and emulsions

(Chinma et al., 2015; Elleuch et al., 2011; Kaur et al., 2012; Sairam et al., 2011; Saunders, 1985). In terms of physiological properties, OBC is believed to absorb oil and fat in the intestinal tract, as well as retain and remove the fat through faeces (Mora et al., 2013). This property is valuable in food product formulations that require good oil retention and cholesterol absorption (T. Wang et al., 2012).

Meanwhile, the SE treatment did not cause major changes to the porosity of RB (Figure 1 O - P; Figure 2 N - O) but increases in the particle size, consequently leading to a decrease in OBC. Our results are in disagreement with the findings reported by Shen et al. (2019), who studied the effect of SE treatment on the extraction and OBC of soluble fibres from black soybean hull. However, their study is not directly comparable with ours as they investigated the oil binding capacity of the soluble fibre fractions, while our study investigated the binding capacity of the total fibre.

CONCLUSION

The US and SE treatments had a significant impact on the physical properties of RB, including particle size, surface microstructure, and BD. The treatments also led to significant changes in the physicochemical properties of the fibre, including WBC, SC, OBC, and colour. The changes in the physicochemical properties of the RB fibre were strongly affected by both the purity of the RB and treatment intensity. This study showed that the purified RB gave clear trends in the relationship between the US and SE treatments received and changes in the physicochemical properties. Purification also allowed the US and SE treatments to work more effectively on RB fibre to bring improvements in its physicochemical properties. Ultrasound brought these changes in the two treatments more effectively than steam explosion. With the knowledge gained from this study, further exploration of the modification of the physicochemical properties of RB by both treatments to vary the application of RB in food products that can enhance the health-promoting properties in the future.

CONFLICT OF 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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