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Effect of Process Variables on Rice Flour Functional Properties, and Porous Structure Properties of Rice and Wheat-Based Leavened Food Products

Running head: Rice Flour Processing for a Well-Porous Crumb

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SUMMARY

Research background. Various processing techniques impart significant impacts on physicochemical and functional properties of rice flour and the quality of the final products. This study aims to modify rice flour from different treatment combinations and to select the best treatment combination in developing rice-wheat-based leavened food products.

Experimental approach. Eight treatment combinations were applied on rice flour according to 2^3 factorial design considering three variables at two levels namely, pre-treatment for rice grain modification [heat-moisture treatment, dual modification treatment (soaking rice grains in a $NaHCO_3$ solution followed by heat treatment)], grinding technique (dry grinding, wet grinding), and flour particle size (75-180 µm, <75 µm). Eight dough samples were prepared by mixing 50 g of rice flour from each treatment with 50 g wheat flour. Thereafter, the dough samples were subjected to fermentation and gelatinization under pressurized condition (externally applied 1.0 kg/cm^2 initial air pressure condition) in a pressure adjustable chamber.

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Results and conclusions. Results rendered that rice flour sample that underwent heat-moisture treatment followed by wet grinding and particle size at 75-180 µm, impart to improve the leavened gas retention capacity and obtaining highly porous and better textured rice-wheat based leavened food products under 1.0 kg/cm^2 externally applied initial air pressure condition.

Novelty and scientific contribution. Rice flour can be modified according to the present method to improve functional flour properties and the textural and structural properties of rice-wheat based leavened food products. Also, conducting fermentation and gelatinization under pressurized condition is a novel food processing technique, which contributes in restricting the escape of leavened gas from rice-wheat composite dough mass.

Key words: factorial design; dry and wet grinding; heat-moisture treatment; particle size; porous crumb structure; rice-wheat composite flour

INTRODUCTION

Rice (*Oryza sativa L*.) is the staple food for about 50 % of the world population covering the majority in Asian countries (*1*). Rice flour is commonly used in various novel as well as traditional food products (*2*). Generally, well-developed porous crumb structure, better physicochemical properties, and acceptable sensorial properties are the main quality parameters that are usually considered in evaluating the quality of leavened food products. Due to the unavailability of gluten proteins, dough samples prepared from rice flour have a poor ability to form a viscoelastic structure that causes to entrap leavening gas during the fermentation. Hence, the development of well-porous crumb structured leavened food products out of rice and other non-glutinous flour is a real challenge. Besides, rice variety, storage condition, grinding technique, flour particle size, damaged starch content, protein, and amylose content, starch modification method, *etc*. can also affect the physicochemical and functional flour properties, thereby affecting the quality and the consistency of the finished products (*3*–*5*). In certain instances, starch modification techniques are also applied in the food industry to overwhelm some baker unfriendly properties in rice flour/ starch to improve the quality of the finished products (*6*).

Heat-moisture treatment (HMT) is a physical starch modification method, of which, a starch-water combination is thermally treated to alter the physicochemical and functional properties of starch in the form of hydration properties, pasting properties, crystallinity, colour and gelatinization enthalpy (*7*–*9*). As proposed by Navaratne (*10*), when rice grains are subjected to HMT, water molecules are penetrated into rice kernels during the period of moisture equilibration. This causes to entangle water molecules with more glucose units (available in starch) by hydrogen bonds through the vibration energy caused during the rapid heat treatment process (80–85 °C; 5 min). Under this circumstance, rice starch would be pre-gelatinized and impart to have a more sticky nature. Hence, HMT flour is more suitable for making bakery products. Additionally, Arns *et al.* (*11*) have also observed that rice grains treated with HMT possessed with lower gelatinization temperature and higher pasting temperature.

A combination of both physical and chemical starch modification processes (dual modification) can also be applied to improve the physicochemical and functional properties of flour. Peries *et al.* (*12*) have shown that, soaking rice grains in 1 M $NaHCO_3$ solution for 1 h followed by washing thoroughly and keeping in an electronic oven at 100 °C for 2 h could improve the functional properties of rice flour. Further, 40 % of rice flour obtained from their study was able to mix with 60 % wheat flour to develop bread with more acceptable organoleptic properties. Generally, the application of $NaHCO_3$ into soaking water can soften the rice kernels and absorb into rice grains. The absorbed $NaHCO_3$ cause to release CO_2 during the heat treatment. The releasing process of the CO_2 gas itself facilitates the formation of more hairy scale cracks over the rice grains. Cracks formed in rice grains makes fine particles during the grinding process. In comparison to HMT, dual modification treatment (DMT) requires a longer heat treatment period to facilitate the formation of cracks in rice grains and to reduce the moisture content of rice grains (because the initial moisture content out of DMT rice grins is high due to immersing in $NaHCO_3$ solution). However, previous studies have not disclosed how the rice grains treated with HMT or DMT combined with grinding technique and particle size would affect the fuctional flour properties and the formation of porous-crumb structure of rice-wheat based leavened food products.

According to our previous study (*13*), conducting the fermentation and gelatinization under an externally applied 1.0 kg/cm^2 initial air pressure condition in a hermetically sealed container contributed to increasing the leavened gas retention capacity of rice-what composite dough samples (rice: wheat in 50:50). Besides, resulting product showed a stable and (less) brittle crumb structure along with a uniform crumb cells distribution.

Under this circumstance, the objective of this study was to modify rice flour using different treatment combinations such as pre-treatments for rice grains modification (heat-moisture treatment and dual modification treatment), size reduction by adapting two grinding techniques (wet grinding and dry grinding), and using two sizes of rice flour particles (75-180 µm particle and <75 µm) with a view of evaluating flour gel hydration properties and improving porous structure properties of rice-wheat based leavened food products prepared under 1.0 kg/cm^2 (externally applied) initial air pressure condition.

MATERIALS AND METHODS

Materials

Certified paddy (BG 300) was obtained from the Rice Research and Development Institute, Bathalegoda, Sri Lanka. Refined wheat flour was purchased from a local supermarket in Colombo Sri Lanka [Prima Ceylon; moisture 13.20 %, protein (dry basis) 11.10 %, particle size <180 µm]. Wheat flour used in the current study was obtained from the same batch. Therefore, the effect of wheat flour on the properties of the crumb samples was assumed as constant. Other major ingredients used in this study include Baker's yeast (Mauripan Instant Dry Yeast, Balakong, Malaysia), table salt (Raigam, Puttalam, Sri Lanka), sugar, shortening (Pyramid Lanka, Colombo, Sri Lanka), and $NaHCO_3$ (Mauri, Balakong, Malaysia, E500(ii)).

PET/LLDPE polymer bags (10 micron P/PET, 50 micron P/LLDPE) were purchased from Acme Printing and Packaging PLC, Piliyandala, Sri Lanka.

Preparation of rice flour samples according to 2^3 factorial design

Paddy was subjected to de-husking and well polishing. Thereafter, eight batches of rice flour were prepared according to 2^3 factorial design considering three variables at two levels namely, pre-treatment for rice grains modification [heat-moisture treatment (HMT) and dual modification treatment (DMT)], grinding technique [dry grinding (DG) and wet grinding (WG)] and flour particle size (75-180 µm and <75 µm particle) as shown in Table 1. Therein, particle size factions of 75-180 µm and <75 µm were selected based on previous studies in literature (*14,15*).

Table 1

Heat-moisture treatment for rice grains

Rice grains were subjected to heat-moisture treatment according to the method described by Navaratne (*10*) with slight modifications. A calculated amount of water was added to rice grains (g) according to Eq. 1 and mixed well in order to make the moisture content of rice around 16.5-17.0 %. Subsequently, rice was packed in an airtight, clean, double-laminated polymer bag (PET/LLDPE) and kept under ambient conditions ((29±2) °C, 68 % RH) for 18-24 h to get the rice at equilibrium moisture content. Thereafter, a sudden heat treatment was given ((85±2) °C) for 4-5 min in a laboratory-scale rotary dryer (Advanced Engineers, Boralesgamuwa, Sri Lanka).

$$m(\text{water})=\left[\frac{w(\text{moisture})_e-w(\text{moisture})_i}{100-w(\text{moisture})_e}\right]\cdot 100 \qquad /1/$$

where $w(\text{moisture})_e$ is equilibrium moisture content that needs to be obtained, $w(\text{moisture})_i$ is initial moisture content of rice grains and $m(\text{water})$ is the amount of water (g) that need to be added to 100 g of rice.

Dual modification treatment for rice grains

Rice grains were subjected to physical and chemical dual modification according to the method described by Peries *et al.* (*12*) with minor alteration. De-husked and well-polished rice grains were dipped in 1 M $NaHCO_3$ solution for 1 h. Thereafter, washed thoroughly and thermally treated in the laboratory-scale rotary dryer (Advanced Engineers, Boralesgamuwa Sri Lanka) at (84±2) °C for 1 h.

Dry grinding and sieving

A portion of the treated rice grains was ground (National, MX-110PN, Osaka, Japan) and sieved using 180 and 75 µm sieves respectively using a sieve shaker (Endecotts, Minor 200, London, United Kingdom) to obtain rice flour with particles in between 75-180 µm and particles less than 75 µm.

Wet grinding and sieving

A portion of treated rice grains was soaked in clean water ((25±2) °C) for 4 h, drained the excess water and ground (National, MX-110PN, Osaka, Japan). Rice flour was dried (UN30, Mammert, Buechenbach Germany) at (55±1) °C for 8 h, and passed through 180 and 75 µm sieves.

Preparation of crumb samples

Eight crumb samples were prepared from each treatment combination (Table 1) according to the method of Rathnayake *et al*. (*13*). Rice-wheat composite flour (rice flour: wheat flour 50:50), salt (1 %) and yeast slurry (which contained dry yeast 2 %, sugar 1.6 %) were mixed while adding lukewarm (40±2) °C water. The dough was kneaded (Sherry, SB-08L, Taichung, Taiwan) for 6 min and thereafter, shortening (2 %) was added while progressing the kneading for another 1 min. Small dough portions of (35±0.05) g (6 dough portions per each treatment combination) were weighted (Axis analytical balance, ALN220, Kartuska, Poland) and placed in cylindrical-shaped sample containers. A thin shortening layer was applied over the dough surface to prevent the case hardening due to the ambient temperature and RH. Thereafter, the dough samples were subjected to fermentation inside a hermetically sealed chamber under pressurized condition created by externally applied air pressure at 1.0 kg/cm^2. After completing the fermentation period of 180 min, the chamber with the samples was heated for 15 min while releasing the pressure inside the chamber gradually parallel to the starch gelatinization process.

Flour gel hydration properties

Approximately (0.50±0.002) g of each flour type was dispersed in 10.00 mL distilled water and agitated in a shaking water bath (Microsil, REX-C700, Ambala Cantt, India) at (80±2) °C for 30 min. Thereafter, the cooked paste was cooled in an ice bath for 10 min and centrifuged (Universal Centrifuge, Hermle, Z 306, Wehingen, Germany) at 3000 rpm for 10 min. The weight of the dry solids was obtained by evaporating the supernatant overnight at (105±2) °C (UN30, Mammert, Buechenbach, Germany). Water absorption index (WAI), water solubility index (WSI) and swelling power (SP) were calculated with reference to the Eqs. 2, 3 and 4 respectively (*3*).

$$\mathrm{WAI}=\frac{m(\text{wet sediment})}{m(\text{flour})} \quad /2/$$

$$\mathrm{WSI}=\frac{m(\text{solids dissolved in supernatant})}{m(\text{flour})}\cdot 100 \quad /3/$$

$$\mathrm{SP}=\frac{m(\text{wet sediment})}{m(\text{flour})-m(\text{solids dissolved in supernatant})} \quad /4/$$

Light microscopy observations

To obtain the light microscopy observations, the flour samples from each treatment combination were suspended in aqueous glycerol (glycerol: H_2O 1:1). A drop of each sample suspension was mounted on a slide and air-dried. The dried samples were strained with iodine and observed (×400) using a light microscope (Optica, B-292, Via Rigla, Italy). The microscopic images were acquired using a 20-Megapixel camera.

Crumb volume, specific volume, and bulk density

The gelatinized crumb samples were cooled at room temperature ((30±1 °C), 68 % RH) for (25±3) min and weighed. Volume/cm^3 of the gelatinized crumb samples was determined following the seed displacement method as per the method described by Aplevicz *et al.* (*16*). Thereafter, specific volume/(cm^3/g) and bulk density/(g/cm^3) of the crumb samples were calculated.

Crumb texture profile analysis

Crumb samples were cooled at room temperature ((30±1) °C, 68 % RH) for (90±3) min and thereafter, texture profile analysis (TPA) was conducted using CT3 Texture profile analyser (Brookfield, M08-372-F1116, Middleboro, MA 02346 USA) along with TexturePro CT Software (*17*), according to the parameters stated by Wang *et al.* (*18*) and Angioloni and Collar (*19*) with some modifications including (20±1) mm sample height, 25 mm diameter probe (TA11/1000), two compression cycles, penetration depth 50 %, trigger load 5 g, test speed 1 mm/s, and load cell 4500 g.

Crumb cellular structure properties (Image analysis)

Crumb cellular structure properties namely, crumb porosity (%), cell density (number of cells/cm^2), average cell area (ACA)/cm^2, cell circularity, and solidity of the scanned images (300 dpi; flatbed scanner, Lide-120, Canon, Tokyo, Japan) of the crumb samples with (3±0.5) mm thickness were evaluated using ImageJ software (*20*). Therein, the scanned images (30 scanned images from each type of the sample) were converted into 8 bit (grayscale), manually thresholded (according to the histogram of grey-level frequencies), and crumb cellular structure properties were analysed with respect to a pre-set scale (cm).

Crumb morphological structure (Fractal Dimension) of the 8 bit, threshold images were analysed following the box-counting method using ImageJ software (*20*) as per the method described by Pérez-Nieto *et al*. (*21*).

Statistical analysis

The data obtained from the study were analysed using Minitab 17.1.0 statistical software (*22*). All the trials were conducted in triplicate and the mean and standard deviation were calculated for each treatment. Analysis of variance (Factorial ANOVA) followed by Tukey pairwise sample comparison were used to compare the mean values at a 95 % confidence level. All the graphs were drawn using Microsoft Excel 2013 (*23*).

RESULTS AND DISCUSSION

Flour gel hydration properties

Results obtained for flour gel hydration properties of the eight treatment combinations in terms of WAI, WSI and SP are illustrated in Fig. 1, and the light microscopy observations of the treatment combinations are presented in Fig. 2. Comparison of WSI (Fig. 1a) and SP (Fig. 1c) of the eight rice flour samples indicated a statistically significant interaction ($p<0.05$) between the three factors (*i.e.*, pre-treatment, grinding technique, and particle size). In addition, pre-treatment and grinding technique showed a significant interaction ($p<0.05$) on WAI values of the eight rice flour treatment combinations (Fig.1b). However, when comparing the overall results for functional properties of the eight rice flour treatment combinations (Fig. 1), rice flour obtained from HMT, DG, and particle size <75 µm (Fig. 2b) showed the highest WAI, WSI, and SP values against the rest of the seven treatment combinations.

Leewatchararongjaroen and Anuntagool (*4*), Heo *et al*. (*24*), and Yoenyongbuddhagal and Noomhorm (*25*) stated that the values obtain for water absorption, water solubility, and swelling power of wet-ground rice flour is lower compared to dry-ground rice flour at temperatures below gelatinization and those values become higher than dry-ground flour at temperatures above gelatinization. According to the results of the current study, a statistically significant interaction ($p<0.05$) was observed among DG samples in all parameters of WSI, WAI, and SP comparatively WG samples. Further, flour samples treated with DG with particle size <75 µm showed significantly high ($p<0.05$) WSI values compared to flour samples with WG and particle size 75-180 µm. Generally, during the dry grinding process, a comparatively considerable amount of starch granules are being damaged due to high mechanical stress and heat energy (*24,26*). When grinding to obtain finer flour particles, higher energy consumption causes higher damage to the starch granules (*27*). Therefore, rice flour with finer particles have higher water absorption, water solubility, and swelling power compared to the rice flour samples with coarser particles (*24,28*). In the case of WSI, rice flour treated with HMT showed a statistically significant interaction ($p<0.05$) with both grinding techniques as well as the particle sizes compared to DMT. Thus, it indicates that the application of DMT significantly ($p<0.05$) caused to reduce the WSI of the rice flour samples against the rice flour samples subjected to HMT.

Swelling power of flour can be highly dependent on the water holding capacity of starches through hydrogen bonds; because hydrogen bonds between starch molecules can be broken with the starch gelatinization process and replaced by the hydrogen bonds between water molecules (*4,29*). As per the results demonstrated in Fig.1c, rice flour obtained from treatment combinations HMT, DG, and particle size 75-180 µm and HMT, DG, and particle size <75 µm demonstrate the highest SP out of all the eight treatment combinations, indicating a statistically significant ($p<0.05$) interaction comparatively other six treatment combinations.

Fig. 1 Fig. 2

Physical properties of the crumb samples

Physical properties of the eight rice-wheat based crumb samples (gelatinized) out of the eight rice flour treatment combinations were compared in order to determine the best treatment combination/s based on the gas retention capacity, textural properties and structural properties of the crumb samples.

Results given in Table 2 relevant to the volume, specific volume and bulk density of eight crumb samples depicted that all the three factors (*i.e.* pre-treatment, grinding technique, and particle size) have a statistically significant interaction (p<0.05). According to post hoc tests with Tukey comparisons, crumb sample prepared from rice flour treatment HMT, WG, and particle size 75-180 µm showed the highest crumb volume, specific volume, and the lowest bulk density compared to the other crumb samples (all p<0.05). Thus, those characteristics demonstrate that the treatment combination HMT, WG, and particle size 75-180 µm having the best leavened gas retention capacity against the rest of the seven treatments.

Furthermore, results depicted in Table 2 demonstrated that the crumb samples prepared from rice flour subjected to wet grinding, having higher crumb volume, specific volume, and lower bulk density values compared to rice flour extracted from dry grinding with the same pre-treatment due to the significant interaction (p<0.05) between pre-treatment and grinding technique. Nevertheless, there was a significant interaction (p<0.05) between particle size and the pre-treatment. This indicates that crumb samples prepared from rice flour with finer particles (<75 µm) having with lower crumb volume, specific volume, and higher bulk density values compared to the crumb samples prepared from rice flour with the same pre-treatment and the particle sizes of 75-180 µm. Hera *et al.* (*15*) have also observed that bread prepared by using rice flour out of short-grains with particle size in between 106-180 µm, had comparatively higher crumb specific volume than the other samples with particle size >180 µm, 106-80 µm, and <80 µm.

Table 2

Texture profile of a leavened food product is mainly depending on the development of crumb cellular structure. Whereas, those attributes play a vital role in determining the consumer's perception of the product quality. According to some aesthetic sensorial properties, food texture is divided into three categories namely, visual texture, auditory texture and tactile texture. Among them, the tactile texture is the most commonly considered textural property of a food product and is the sensation of direct contact between the food and human skin either by hand or by oral surface (*30,31*). Table 3 depicts the results of the texture profile analysis of the eight crumb samples prepared from the eight treatment combinations. According to those findings, a statistically significant interaction (p<0.05) could be observed between all the three factors (*i.e.* pre-treatment, grinding technique and particle size) in crumb hardness, gumminess and chewiness. Therein, the crumb sample prepared from the treatment HMT, WG, and particle size 75-180 µm showed the lowest values compared to the rest of the seven crumb samples.

Springiness is the ability of a sample to bounce back to its original position after completing a compressive force (*32,33*). Eight crumb samples did not show a significant interaction (p>0.05) across the three factors (Table 3). However, crumb samples prepared from rice flour treated with DMT and flour particle size 75-180 µm showed the highest values for springiness.

Results further indicated that the crumb sample prepared from treatment combination DMT, WG, and particle size <75 µm contributed to having the highest cohesiveness value, as shown in Table 3. However, this value is not significantly different (p>0.05) from the cohesiveness value of the crumb sample prepared from HMT, WG, and particle size 75-180 µm. This high cohesiveness value also proves that rice flour obtained from this treatment imparting to having a higher specific volume and lower crumb hardness values.

According to Araki *et al.* (*34*), if the amount of damaged starch granules content is low, the WAI of rice flour is also low and the bakery products prepared from these types of flour can result in higher crumb specific volume with better crumb textural properties. The results of the current study (Fig. 1 and Tables 2 and 3) also indicated that rice flour treatments with HMT and WG having the lowest WAI values along with the highest crumb volume, specific volume and the lowest bulk density, hardness, gumminess and chewiness values. Moreover, the results obtained from the current study further demonstrated that the interaction between the rice flour treatment combinations relevant to WG and flour particle size 75-180 µm contributed to obtaining the highest (p<0.05) crumb specific volume along with the lowest hardness, gumminess and chewiness values in rice-wheat based leavened products.

Table 3

When a leavened baked product is sliced, a two-phase soft cellular solid structure can be seen. This includes a solid phase made out of the cell wall structure along with a fluid phase that consists of air (*35,36*). Recently, image analysis has become an important quantitative tool to reliably assess the microstructural features of crumb samples and to assist the relationship of crumb cellular structure properties to the mechanical and organoleptic properties of the product (*35,37*). Scanned images of the crumb samples (300 dpi) prepared from eight rice flour treatment combinations are illustrated in Fig. 3. The results obtained from crumb cellular structure analysis (image analysis) of the eight crumb samples are demonstrated in Table 4.

Table 4 Fig. 3

According to Korczyk-Szabó and Lacko-Bartošová (*36*) and Lassoued *et al.* (*38*), a well-developed porous crumb structure is represented by having a higher porosity along with a finer and regular gas cell structure. Crumb porosity is the average value of the total cells to the total area ratio on a pre-designed volume of a sample. If higher the porosity, the higher the number of gas cells that have a diameter of >1mm, and the lower the degree of cell uniformity. Cell density and cell circularity are also other important factors that assess the properties of crumb cellular structure. Generally, cell density is defined as the number of cells per unit area; where, If higher the cell density, the finer the crumb cellular structure (*39*). Cell circularity is identified as a shape factor that ranges from 0 (line) to 1 (perfect circle) to represent the shape of a gas cell (*40*). However, due to the complex mechanical behaviour of the porous crumb structure, considerable structural variations can be observed even within different slices of a single sample (*41*). The morphology of those types of objects can be evaluated through the Fractal dimension (FD), where higher FD values represent rougher or complex grey-level images (*21,42*).

When considering the results given in Table 4, The statistical interaction between the three factors were not significantly different (p>0.05) in crumb porosity, average cell area (ACA), cell circularity, and FD. However, according to the Tukey pairwise comparison, crumb samples prepared from treatment combinations of “HMT, DM, and particle size 75-180 µm”, “HMT, WG, and particle size 75-180 µm, and “HMT, WG, and particle size <75 µm” had higher crumb porosity, ACA, cell circularity, solidity, FD and lower cell density values comparatively the rest of the crumb samples. Further, crumb samples from the treatments of HMT and WG depicted significantly high (p<0.05) porosity and ACA against all the other crumb samples. Scanned images (Fig. 3) of the crumb samples also proved these observations for obtaining crumb samples with highly porous crumb structure with larger, circular, and solid gas cells when treated rice flour by HMT and WG.

As far as overall results from the current study are concerned, it proves that rice flour obtained from heat-moisture treating rice grains followed by wet grinding and particle size 75-180 µm can be applied successfully in developing rice-wheat based bakery products (rice: wheat, 50:50), particularly using *indica* rice varieties. So also, conducting fermentation and gelatinization of rice-wheat composite dough samples under pressurized condition is a new approach for the baking industry as usually these two processes are performed under open air condition. Because this method is capable of arresting leaven gas during fermentation as rice flour is devoid of gluten protein. Thus, causes to improve textural and structural properties of the final product.

CONCLUSIONS

Different treatment combinations that include pre-treatment for rice grain modification, grinding technique and rice flour particle size remarkably contribute to rice flour functional properties as well as the development of the porous-crumb structure of rice-wheat based leavened food products (rice: wheat, 50:50). Treating rice grains with HMT followed by WG impart to have better crumb volume and better texture properties in rice-wheat based leavened food products along with having a highly porous crumb structure with larger, circular, and solid gas cells compared to the treatment combinations with DMT and DG. Moreover, size reduction by WG in order to get particle size 75-180 µm also positively contribute to having higher crumb volume and lower bulk density against DG to obtain particles size <75 µm in rice-wheat based dough samples. Altogether, the current study suggest that the treatment combination “HMT, WG, and particle size 75-180 µm” provides an appropriate combination along with 50% refined wheat flour in developing highly porous and better textured rice-wheat based leavened food products with higher gas retention capacity. However, to obtain these results fermentation and gelatinization must be practised under 1.0 kg/cm^2 externally applied initial air pressure condition.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest regarding this publication.

AUTHORS' CONTRIBUTION

H. A. Rathnayake and S. B. Navaratne designed and performed the study. H. A. Rathnayake collected and analysed the data and drafted the manuscript. S. B. Navaratne and C. M. Navaratne edited and revised the manuscript.

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Table 1. Eight rice flour treatment combinations according to 2^3 factorial design

Treatment number	Treatment combination
1	HMT, DG, and particle size 75-180 µm
2	HMT, DG, and particle size <75 µm
3	HMT, WG, and particle size 75-180 µm
4	HMT, WG, and particle size <75 µm
5	DMT, DG, and particle size 75-180 µm
6	DMT, DG, and particle size <75 µm
7	DMT, WG, and particle size 75-180 µm
8	DMT, WG, and particle size <75 µm

HMT=heat moisture treatment, DMT=dual modification treatment, DG=dry grinding, WG=wet grinding

Table 2. Volume, specific volume, and bulk density of the crumb samples prepared from eight rice flour treatment combinations

Rice flour treatment combination	V(crumb)/cm^3	v(crumb)/(cm^3/g)	ρ_b(crumb)/(g/cm^3)
Pre-treatment*Grinding technique	**	**	**
HMT DG	45.101^c	1.640^c	0.518^c
HMT WG	54.564^a	1.951^a	0.625^a
DMT DG	44.750^c	1.580^d	0.633^a
DMT WG	48.640^b	1.734^b	0.580^b
Pre-treatment*Particle size	**	**	**
HMT 75-180 µm	54.723^a	1.966^a	0.510^c
HMT <75 µm	44.943^c	1.625^c	0.633^a
DMT 75-180 µm	48.343^b	1.733^b	0.581^a
DMT <75 µm	45.047^c	1.581^d	0.633^a
Grinding technique* Particle size	--	--	--
DG 75-180 µm	48.052^b	1.723^b	0.584^b
DG <75 µm	41.800^c	1.498^c	0.674^a
WG 75-180 µm	55.013^a	1.976^a	0.507^c

WG <75 µm	48.191[b]	1.708[b]	0.591[b]
Pre-treatment*Grinding technique*Particle size	**	**	**
HMT DG 75-180 µm	(51.247±0.450)[b]	(1.852±0.021)[b]	(0.541±0.006)[c]
HMT DG <75 µm	(38.955±0.851)[d]	(1.430±0.025)[d]	(0.709±0.022)[a]
HMT WG 75-180 µm	(58.198±0.799)[a]	(2.081±0.029)[a]	(0.480±0.007)[d]
HMT WG <75 µm	(50.930±0.757)[b]	(1.821±0.012)[b]	(0.556±0.011)[c]
DMT DG 75-180 µm	(44.867±0.611)[c]	(1.594±0.015)[c]	(0.627±0.006)[b]
DMT DG <75 µm	(44.642±0.363)[c]	(1.566±0.014)[c]	(0.639±0.011)[b]
DMT WG 75-180 µm	(51.828±0.333)[b]	(1.872±0.013)[b]	(0.534±0.004)[c]
DMT WG <75 µm	(45.452±0.809)[c]	(1.597±0.046)[c]	(0.627±0.018)[b]

Mean values in the same column with different superscripts are significantly different at 0.05 significant level according to Factorial ANOVA followed by Tukey pairwise comparison. *Interaction effect, **interaction effect is significant at 0.05 significant level, --interaction effect is not significant at 0.05 significant level. HMT=heat moisture treatment, DMT=dual modification treatment, DG=dry grinding, WG=wet grinding, 75-180 µm and <75 µm=rice flour particle size

Table 3. Texture profile analysis of the crumb samples prepared from eight rice flour treatment combination

Rice flour treatment combination	Hardness/g	Springiness/mm	Cohesiveness	Gumminess/g	Chewiness/mJ
Pre-treatment*Grinding technique	**	--	**	**	**
HMT DG	3482.21[a]	9.755[a]	0.485[b]	1664.33[a]	163.831[a]
HMT WG	1543.89[d]	9.849[a]	0.548[a]	848.44[c]	82.018[c]
DMT DG	2652.75[c]	9.755[a]	0.563[a]	1410.29[b]	134.873[b]
DMT WG	2898.50[b]	9.622[a]	0.571[a]	1582.77[a]	146.517[b]
Pre-treatment*Particle size	**	**	**	--	**
HMT 75-180 µm	1666.21[c]	9.729[ab]	0.545[b]	904.88[d]	85.91[2c]
HMT <75 µm	3359.89[a]	9.8751[a]	0.488[c]	1607.89[b]	159.938[a]
DMT 75-180 µm	2261.92[b]	10.020[a]	0.558[ab]	1203.04[c]	119.788[b]
DMT <75 µm	3289.33[a]	9.413[b]	0.576[a]	1790.02[a]	161.602[a]
Grinding technique* Particle size	**	--	**	**	**
DG 75-180 µm	2136.07[c]	9.924[a]	0.548[a]	1124.05[c]	94.828[c]
DG <75 µm	3998.89[a]	9.642[a]	0.500[b]	1950.57[a]	133.707[b]
WG 75-180 µm	1792.06[d]	9.825[a]	0.555[a]	983.87[d]	110.871[c]
WG <75 µm	2650.33[b]	9.645[a]	0.564[a]	1447.33[b]	187.834[a]

Pre-treatment*Grinding technique*Particle size	**	--	**	**	**
HMT DG 75-180 µm	(2027.10±191.60)^{de}	(9.697±0.449)^{ab}	(0.520±0.033)^{c}	(1068.90±148.40)^{de}	(101.190±10.680)^{cd}
HMT DG <75 µm	(4937.30±157.30)^{a}	(9.814±0.298)^{ab}	(0.450±0.013)^{d}	(2259.80±32.50)^{a}	(226.480±8.830)^{a}
HMT WG 75-180 µm	(1305.30±94.10)^{f}	(9.761±0.656)^{ab}	(0.570±0.031)^{ab}	(740.90±34.50)^{f}	(70.640±2.920)^{e}
HMT WG <75 µm	(1782.50±55.30)^{e}	(9.937±0.162)^{ab}	(0.527±0.039)^{c}	(956.00±80.00)^{e}	(93.400±7.900)^{de}
DMT DG 75-180 µm	(2245.00±224.30)^{d}	(10.150±0.352)^{a}	(0.577±0.015)^{ab}	(1179.20±74.20)^{d}	(120.550±15.220)^{c}
DMT DG <75 µm	(3060.50±194.90)^{c}	(9.472±0.290)^{b}	(0.550±0.008)^{bc}	(1641.40±149.00)^{c}	(149.190±16.420)^{b}
DMT WG 75-180 µm	(2278.80±250.30)^{d}	(9.890±0.273)^{ab}	(0.540±0.006)^{bc}	(1226.90±141.00)^{d}	(119.020±15.320)^{c}
DMT WG <75 µm	(3518.20±199.50)^{b}	(9.353±0.433)^{b}	(0.602±0.010)^{a}	(1938.60±215.90)^{b}	(174.000±26.400)^{b}

Mean values in the same column with different superscripts are significantly different at 0.05 significant level according to Factorial ANOVA followed by Tukey pairwise comparison. *Interaction effect, **interaction effect is significant at 0.05 significant level, --interaction effect is not significant at 0.05 significant level. HMT=heat moisture treatment, DMT=dual modification treatment, DG=dry grinding, WG=wet grinding, 75-180 µm and <75 µm=rice flour particle size

Table 4. Cellular structure properties (Image analysis) of the crumb samples prepared from eight rice flour treatment combinations

Rice flour treatment combination	Porosity/%	Cell density/(Number of cells/cm^2)	ACA/cm^2	Circularity	Solidity	FD
Pre-treatment*Grinding technique	**	--	**	--	--	--
HMT DG	24.331^c	29.502^b	0.009^{bc}	0.492^b	0.708^b	1.648^b
HMT WG	32.56^a	27.208^c	0.012^a	0.509^a	0.729^a	1.664^a
DMT DG	24.635^c	31.723^a	0.008^c	0.475^c	0.690^c	1.652^b
DMT WG	27.843^b	29.502^b	0.010^b	0.481^{bc}	0.704^b	1.648^b
Pre-treatment*Particle size	**	**	**	--	--	**
HMT 75-180 µm	31.938^a	31.823^a	0.013^a	0.500^a	0.728^a	1.658^b
HMT <75 µm	24.954^b	29.402^b	0.008^b	0.501^a	0.709^b	1.642^c
DMT 75-180 µm	26.318^b	25.562^c	0.009^b	0.482^b	0.701^{bc}	1.658^b
DMT <75 µm	24.954^b	29.402^b	0.009^b	0.473^b	0.693^c	1.661^{ab}
Grinding technique* Particle size	**	--	**	--	**	**
DG 75-180 µm	27.410^b	29.612^b	0.010^b	0.487^{ab}	0.710^a	1.668^a
DG <75 µm	21.557^c	31.715^a	0.007^c	0.481^b	0.688^b	1.632^b
WG 75-180 µm	30.846^a	27.773^c	0.012^a	0.496^a	0.718^a	1.661^a

WG <75 µm	28.557[a]	28.937[bc]	0.011[ab]	0.494[ab]	0.714[a]	1.671[a]
Pre-treatment*Grinding technique*Particle size	--	**	--	--	**	--
HMT DG 75-180 µm	(29.088±2.339)[bc]	(25.309±1.997)[c]	(0.012±0.002)[ab]	(0.496±0.027)[abc]	(0.725±0.014)[ab]	(1.671±0.025)[ab]
HMT DG <75 µm	(19.576±3.174)[f]	(33.899±1.798)[a]	(0.006±0.002)[d]	(0.489±0.031)[bcd]	(0.690±0.015)[cd]	(1.625±0.023)[d]
HMT WG 75-180 µm	(34.788±3.012)[a]	(25.814±2.141)[c]	(0.014±0.003)[a]	(0.504±0.038)[ab]	(0.730±0.017)[a]	(1.670±0.014)[ab]
HMT WG <75 µm	(30.332±1.890)[b]	(28.602±2.314)[b]	(0.011±0.003)[ab]	(0.513±0.024)[a]	(0.727±0.008)[a]	(1.659±0.018)[bc]
DMT DG 75-180 µm	(25.733±2.446)[de]	(33.914±2.396)[a]	(0.008±0.002)[cd]	(0.478±0.033)[cd]	(0.696±0.017)[cd]	(1.665±0.019)[ab]
DMT DG <75 µm	(23.538±2.433)[e]	(29.532±2.716)[b]	(0.008±0.002)[cd]	(0.472±0.034)[d]	(0.685±0.021)[d]	(1.639±0.009)[cd]
DMT WG 75-180 µm	(26.904±2.617)[cd]	(29.732±2.591)[b]	(0.009±0.002)[bc]	(0.487±0.040)[bcd]	(0.706±0.024)[bc]	(1.652±0.012)[bc]
DMT WG <75 µm	(28.781±2.171)[bc]	(29.272±2.560)[b]	(0.010±0.002)[bc]	(0.474±0.027)[cd]	(0.701±0.015)[cd]	(1.684±0.017)[a]

Mean values in the same column with different superscripts are significantly different at 0.05 significant level according to Factorial ANOVA followed by Tukey pairwise comparison. *Interaction effect, **interaction effect is significant at 0.05 significant level, --interaction effect is not significant at 0.05 significant level. HMT=heat moisture treatment, DMT=dual modification treatment, DG=dry grinding, WG=wet grinding, 75-180 µm and <75 µm=rice flour particle size

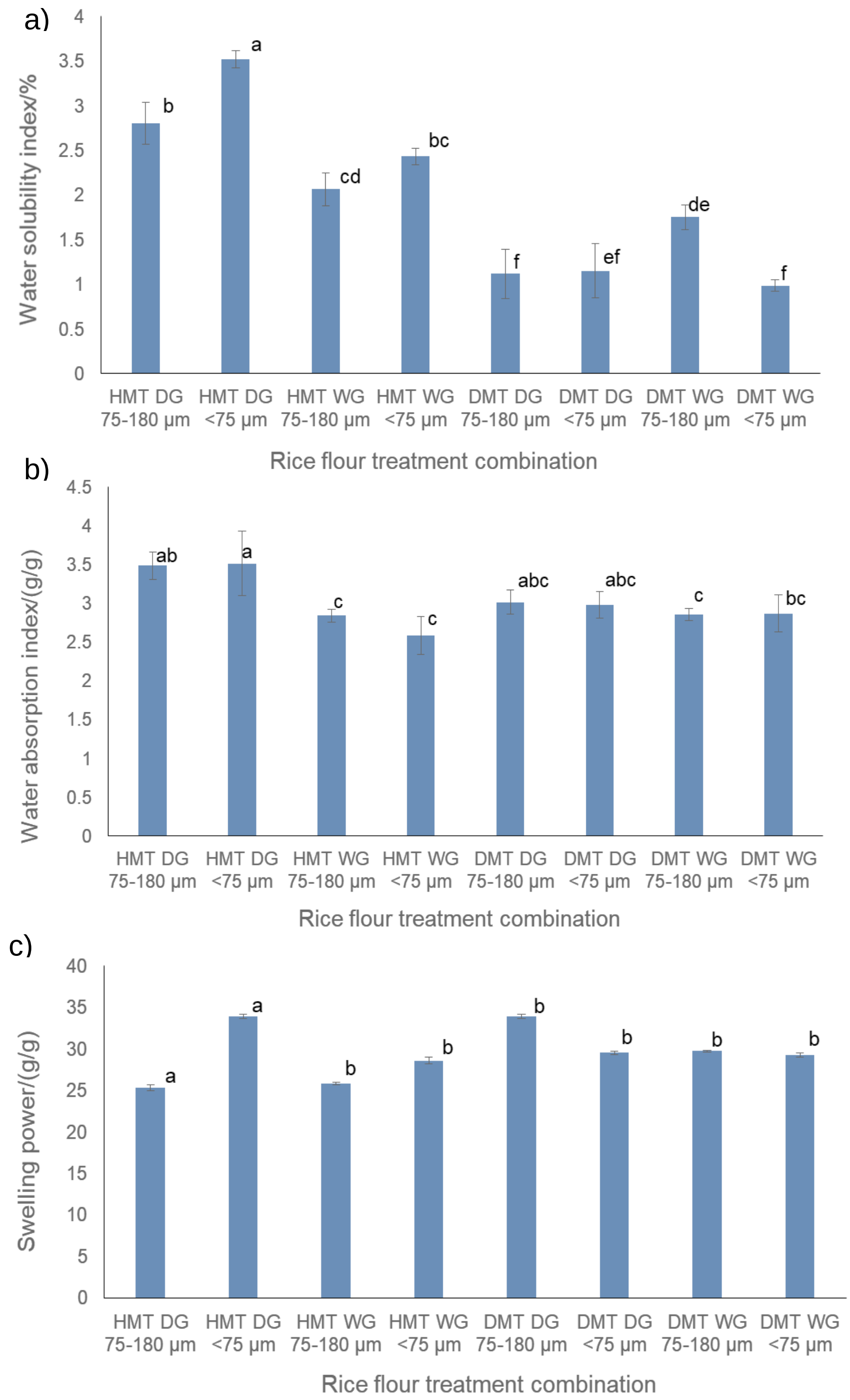

Fig. 1. Gel hydration properties of the eight rice flour treatment combinations: a) water solubility index (WSI), b) water absorption index (WAI) and c) swelling power. Results are represented as mean±S.D. of replicates (n=3); mean values in the same plot with different superscripts are significantly different

at 0.05 significant level. HMT=heat moisture treatment, DMT=dual modification treatment, DG=dry grinding, WG=wet grinding, 75-180 µm and <75 µm=rice flour particle size

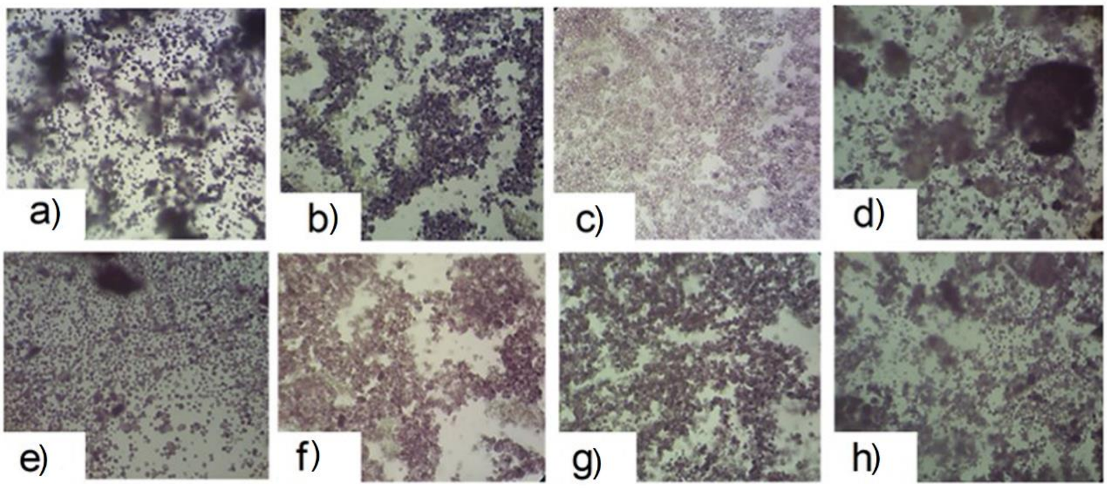

Fig. 2. Light microscopy observations of rice flour obtained from eight treatment combinations (magnification: 400×): a) HMT, DG, and particle size 75-180 µm, b) HMT, DG, and particle size <75 µm, c) HMT, WG, and particle size 75-180 µm, d) HMT, WG, and particle size <75 µm, e) DMT, DG, and particle size 75-180 µm, f) DMT, DG, and particle size <75 µm, g) DMT, WG, and particle size 75-180 µm, and h) DMT, WG, and particle size <75 µm. HMT=heat moisture treatment, DMT=dual modification treatment, DG=dry grinding, WG=wet grinding

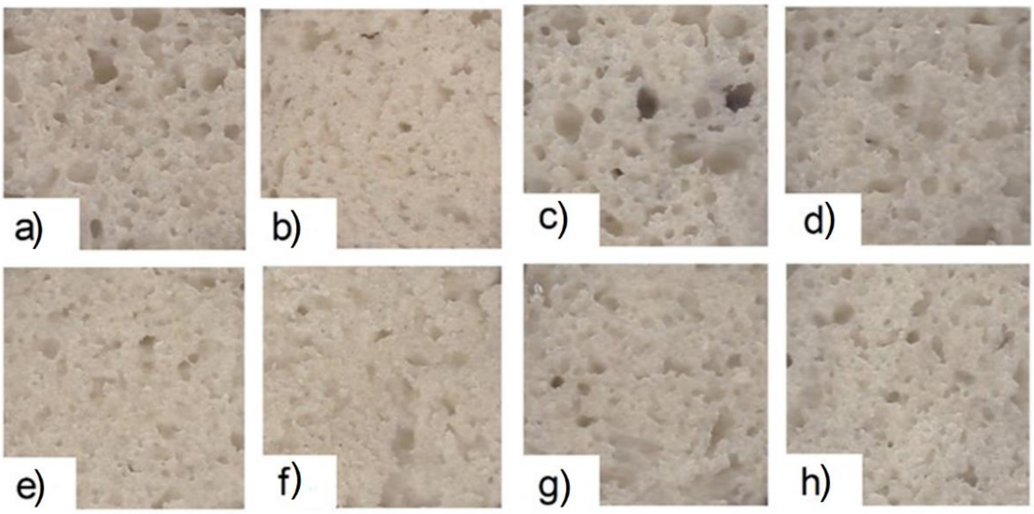

Fig. 3. Scanned images (300 dpi) of the porous structure of the crumb samples prepared from eight rice flour treatment combinations, a) HMT, DG, and particle size 75-180 µm, b) HMT, DG, and particle size <75 µm, c) HMT, WG, and particle size 75-180 µm, d) HMT, WG, and particle size <75 µm, e) DMT, DG, and particle size 75-180 µm, f) DMT, DG, and particle size <75 µm, g) DMT, WG, and particle size 75-180 µm, and h) DMT, WG, and particle size <75 µm. HMT=heat moisture treatment, DMT=dual modification treatment, DG=dry grinding, WG=wet grinding