Received: 26 February 2019 | Revised: 29 June 2019 | Accepted: 2 July 2019

DOI: 10.1111/jtxs.12465

RESEARCH ARTICLE

Journal of Texture Studies WILEY

# Improving porous crumb structure of rice-related leavened food products by fermentation and gelatinization at slightly higher air pressure conditions

Heshani A. Rathnayake[1] | Senevirathne Navaratne[1] | Champa Navaratne[2]

[1]Department of Food Science and Technology, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka

[2]Department of Agricultural Engineering, Faculty of Agriculture, University of Ruhuna, Kamburupitiya, Sri Lanka

**Correspondence**
Heshani A. Rathnayake, Department of Food Science and Technology, Faculty of Applied Sciences, University of Sri Jayewardenepura, Gangodawilla, Nugegoda, Sri Lanka.
Email: heshani@sci.sjp.ac.lk

**Funding information**
National Science Foundation, Grant/Award Number: TG/2017/Tech-D/03

## Abstract

Porous crumb structure of rice-related leavened food products developed under air pressure conditions during fermentation and gelatinization in a fabricated fermentation chamber were characterized. Therein, four samples were prepared under three pressurized conditions (sample pressurized by the leavened gas itself, 1 kg/cm$^2$ initial pressure, 1.5 kg/cm$^2$ initial pressure) along with a control (unpressurized). Crumb volume, specific volume, bulk density, pH as well as crumb texture profile and cellular structure were analyzed. Results revealed that fermentation and gelatinization under air pressure (slightly higher than the atmospheric air pressure) conditions in the fabricated fermentation chamber help to arrest leavening gas within the dough mass to improve the properties of porous crumb structure. Sample fermented and gelatinized at 1 kg/cm$^2$ initial pressure presented better crumb mechanical and cellular structural properties compared to the other two pressurized samples and the control.

**KEYWORDS**
crumb structure, dough fermentation, gas retention, porosity, rice flour, texture

## 1 | INTRODUCTION

Bread and other leavened baked products are commonly consumed on everyday basis throughout the world (Ballesteros López, Guimarães Pereira, & Junqueira, 2004). As far as food acceptability of leavened baked products is concerned, well-developed porous crumb structure along with better physicochemical and sensorial properties have become popular parameters among the consumers in the dynamic food market. Porous crumb structure consists of crumb grains which can be described as the exposed cellular structure when a leavened baked product is sliced. Porous crumb structure development depends on dough ingredients, processing conditions, relative humidity, and temperature during fermentation, yeast activity, and gas bubble formation (Rathnayake, Navaratne, & Navaratne, 2018).

Wheat flour is the most commonly used ingredient in leavened baked products. However, the reduction of wheat flour usage and application of composite flour had gained the interest among cereal scientists due to health (for celiac disease population), nutritional, and economic reasons. When considering the economical aspects, wheat is not grown in Sri Lanka and the entire requirement is imported. Around 1,250,000 Metric Tons of wheat grains had been imported in 2017 (Central Bank of Sri Lanka, 2018; Department of Census and Statistics, 2018) spending around 46,239 million Sri Lankan rupees (Department of Census and Statistics, 2018) causing a sever burden for the national coffer.

Rice (*Oryza sativa L.*) is the major staple food in Sri Lanka as well as the majority of the Asian countries that is an important source of nutrition and energy which provides 40% total protein and 45% calorie requirement of an average Sri Lankan (Fari, Rajapaksa, & Ranaweera, 2010). Many researchers have identified rice flour as one of the most important flours for substituting wheat flour in developing leavened baked products due to its nonallergenic nature, trivial flavor, low sodium content, and pale appearance (Mancebo, Merino,

This article was published on AA publication on: 8 July 2019

  

Martínez, & Gómez, 2015; Sanchez, Osella, & La Torre, 2002). The major barrier in developing rice based leavened products is its poor ability to produce a viscoelastic structure for entrapping the leavened gas within the dough mass itself. Because, not like wheat flour, rice flour contains little amount of prolamins (2.5–3.5%) (Gujral & Rosell, 2004) and also those are non-gluten prolamins (Balakireva & Zamyatnin, 2016).

There are several studies in literature regarding the application of rice flour in leavened baked products in composite flour mixes with or without incorporating wheat flour (Sasaki, Kohyama, Miyashita, & Okunishi, 2014; Yamauchi et al., 2004). Fari et al. (2010) have substituted wheat flour by 30% rice flour for their study and declared that 30% rice flour imparts the best quality attribute in terms of specific volume and crumb structure of the leavened products. Some other researchers have incorporated different food hydrocolloids (such as, guar gum, carboxymethylcellulose (CMC), locust bean gum, and agarose (Wang, Lu, Li, Zhao, & Han, 2017), hydroxypropylmethylcellulose (HPMC) (Hager & Arendt, 2013)) as well as emulsifiers (Eduardo, Svanberg, & Ahrné, 2014; Onyango, Unbehend, & Lindhauer, 2009), enzymes (Błaszczak, Sadowska, Rosell, & Fornal, 2004; Gray & Bemiller, 2003), algal proteins (Różyło, Hameed Hassoon, Gawlik-Dziki, Siastała, & Dziki, 2017) to obtain leavened baked products with well developed porous crumb structure and antistaling properties.

According to the United States Patent No. US1923880A, (1930), fermentation under pressurized conditions (created either by mechanically or by the leavened gas itself) can reduce the time required for the production of a well porous crumb structure, develop the gluten more rapidly and produce a palatable flavor in the final product prepared from wheat flour.

When a fermented dough is subjected to heating, the major physical changes occur at the temperature range in between 60 and 85°C that convert a dough to a crumb as a result of protein denaturation and starch gelatinization (Mondal & Datta, 2008). Meanwhile, thermal expansion of vapor occurs within the dough mass and the saturation water pressure increases with parallel to the temperature increment. As a result, the pressure inside the gas cells get increased causing the dough to be expanded (Jefferson, Lacey, & Sadd, 2007). Hayman, Hoseney, and Faubion (1998) have mentioned that a dough get expanded reaching the maximum expansion volume during the first 6–8 min of heating. As a result of the pressure increment within the crumb grains, fracturing occurs by coalescing the gas cells (Hayman et al., 1998; Jefferson et al., 2007). This can create a poorly developed porous crumb structure with larger gas cells with thick cell walls (Hayman et al., 1998). To prevent the occurrence of gas cell failure under this rapid expansion and to result fine and more uniform crumb grains, Hayman et al. (1998) have suggested that there should be a better balance between the viscous and elastic properties of the medium around the gas cells. Further, according to Cauvain and Young (2009), controlled and uniform dough expansion during heating is also have a considerable relation with dough gas retention ability.

The purpose of the current study is to develop rice related crumb samples by conducting the fermentation and gelatinization in a pressure controllable prototype fermentation chamber at different air pressure conditions while releasing the pressure with parallel to the starch gelatinization process. Further, this study aims to evaluate textural and cellular structural properties of the formed products compared to a control with a view to determine the effect of different air pressure conditions on leavened gas retention and porous crumb structure development in rice related leavened food products.

## 2 | MATERIALS AND METHODS

### 2.1 | Materials and rice flour preparation

Cleaned, free from insect attack and well-polished rice was purchased from a registered local supplier (Rathna Rice Mill and Food product, Horana, Sri Lanka). Purchased rice were steeped in excess amount of water at 25 ± 2°C for 4 hr, grounded by household grinder (National Grinder, MX 110PN), dried in a hot air oven at 45 ± 2°C for 6 hr (Universal oven, Mammert, UN 30) and sieved to take particles less than 180 μm (Sieve shaker, Endicotts, minor 200). Other ingredients such as, wheat flour (Prima; particles less than 180 μm), dry yeast (Mauripan instant dry yeast), table salt, sugar, and shortening were purchased from registered supermarket chains in Colombo, Sri Lanka.

### 2.2 | Sample preparation

Yeast slurry was prepared by mixing 2.0 g/100 g flour basis of dry yeast and 1.6 g/100 g sugar along with some lukewarm water (40 ± 2°C) and added to the flour mixture that contains 50.0 g/100 g rice flour and 50.0 g/100 g wheat flour. Thereafter 1.0 g/100 g salt was added to the flour mixture and mixed by adding lukewarm water until the whole water content becomes 60 mL/100 g. Then the dough was kneaded (Dough mixer, SB-08L) for 6 min and 2.0 g/100 g shortening was incorporated and kneaded again for 1 min. Then the dough was divided into small dough portions of 20 ± 0.05 g (electronic balance, KERM ABJ-NM/ABS-N, ABS 220-4N, Max 220 g, $d$ = 0.1 mg) shaped and inserted into cylindrical containers (Ø 32.0 mm × 138.0 mm [H]) and a thin fat (shortening) layer was applied over the exposed surface of the samples. Thereafter the samples were subjected to fermentation and gelatinization under different initial pressure conditions as mentioned in Table 1 in a prototype fermentation chamber (Figure 1). Heat treatment was given for the pressurized samples (P1, P2, and P3) (after 180 min of fermentation at 30 ± 1°C) and subjected to gelatinize the dough samples in the fermentation chamber itself for 15 min while gradually releasing the pressure inside the

**TABLE 1** Pressurized conditions in the chamber

| Sample | Pressure condition inside the chamber |
|---|---|
| P1 | Sample pressurized by the leavened gas itself |
| P2 | Application of 1 kg/cm$^2$ initial pressure before fermentation |
| P3 | Application of 1.5 kg/cm$^2$ initial pressure before fermentation |
| C | Sample prepared without pressure application |

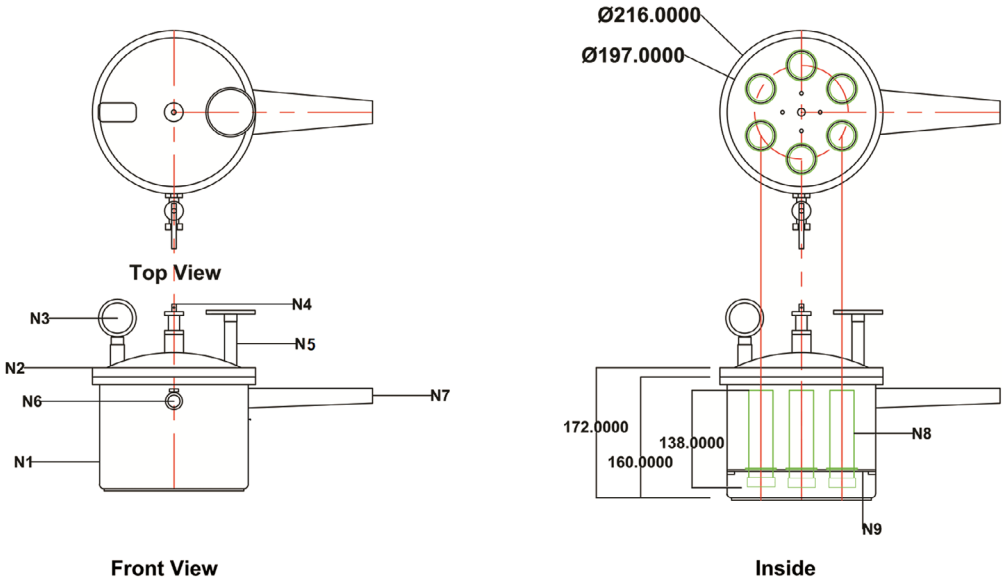


**FIGURE 1** General structure of prototype design of the fermentation chamber: N1 = vessel, N2 = lid, N3 = pressure gauge, N4 = safety valve, N5 = temperature gauge, N6 = pressure adjustable valve, N7 = handle, N8 = cylindrical containers, N9 = tray

chamber with parallel to the starch gelatinization process. The control sample (C; unpressurized) was also heated and subjected to gelatinization process for 30 min without pressure conditions.

## 2.3 | Fermentation chamber

Figure 1 depicts the prototype fermentation chamber which was used to develop crumb samples. The temperature and pressure inside the vessel were detected using pressure (N3) and temperature gauges (N4). Application of initial air pressure was done through the pressure adjustable valve (N6) on the vessel using an air compressor.

## 2.4 | Crumb volume, specific volume, and bulk density

The gelatinized crumb samples were cooled for 25 min at room temperature (30 ± 1°C, 68% RH) and weighed. Thereafter, crumb volume ($cm^3$) was determined using rapeseed displacement method and the specific volume ($cm^3/g$) was calculated as a ratio of crumb volume ($cm^3$) to the crumb weight (g). Further, bulk density of the crumb samples (g $cm^{-3}$) was obtained by the ratio between crumb weight (g) and crumb volume ($cm^3$).

## 2.5 | Crumb pH

Approximately 5 ± 0.05 g of each crumb sample was measured and added to 50 mL of distilled water (27 ± 2°C) as small fractions. Thereafter, suspends were shaken well and let the samples stand for 30 min. The pH of the supernatant was determined using Adwa pH/MV and temperature meter (AD 1030).

## 2.6 | Texture profile analysis

The crumb samples were cooled for 90 min at room temperature (30 ± 1°C, 68% RH) and sliced using a paper cutter into 20 ± 0.5 mm height. Thereafter, texture profile analysis (TPA) was done (CT3 Texture profile analyzer, M08-372-F1116) according to the parameters mentioned by Angioloni and Collar (2009) and Wang, Rosell, and Barber (2002) with slight modifications concerning two compression cycles, probe with 25 mm diameter (TA11/1000), Deformation 50%, test speed 1 mm/s, Trigger load 5 g, Load cell 4,500 g. Results were obtained in Brookfield TexturePro CT Software TA-CT-PAD-AY.

## 2.7 | Image analysis

The crumb samples were cut into slices of about 3 ± 0.5 mm thickness and scanned (flatbed scanner, Canon Lide-120) under the resolution of 300 dpi and the resulting images were saved as JPEG files. Thereafter the obtained images (30 images from each sample type) were threshold and analyzed using ImageJ software as described by Pérez-Nieto et al. (2010) with some modifications. Initially, the scale of the values were set for "cm" prior to taking the measurements. Then, an exact area of the scanned images was selected, cropped from the image center and converted into a grayscale (8 bit) image. The images were manually threshold with respect to the histogram of gray-level frequencies. Thereafter, crumb porosity (%) (Void fraction), cell density (cells/$cm^2$), average cell area (ACA) ($cm^2$), cell circularity and solidity were determined.

Fractal dimension (FD) was measured following the box-counting method using ImageJ software using 2D, 8bit, threshold images by the slope of the least-squares linear regression of the log (box count) vs. log (box size) plot [Equation (1)] (Pérez-Nieto et al., 2010). Therein, "*N*" represents the number of boxes and "*r*" represents the length of the side of the box.

$$FD = \frac{\log(N)}{\log(1/r)} \quad (1)$$

### 2.8 | Statistical analysis

All experiments were carried out in triplicate and the parametric results were analyzed using one way ANOVA followed by Tukey sample comparison using Minitab 17 statistical software. All the statistical evaluations were conducted under the confidence interval of 95%.

## 3 | RESULTS AND DISCUSSION

Crumb physical properties (Quality Characterization) of the four samples are given in Table 2. Figure 2 represents the cross sections of the four crumb samples whereas crumb cellular structure properties of them are given in Table 3.

Crumb volume represents the capability of retaining leavened gas within the dough mass (Onyango et al., 2009) as well as it is an important quantitative parameter for baking performance (Maktouf et al., 2016; Mondal & Datta, 2008). Crumb specific volume ($cm^3/g$) is related to crumb hardness and relative elasticity (Scanlon & Zghal, 2001). Whereas, bulk density ($g/cm^3$) is mostly used to describe the density of crumb cellular solid (Scanlon & Zghal, 2001). According to the Table 2, sample P2 has the highest volume, specific volume as well as the lowest bulk density that are significantly different ($p \leq .05$) to P1 and C. Hence, it could be concluded that the sample P2 had shown comparatively improved leavened gas retention capability than P1 and C.

Analysis of crumb texture profile highly depends on crumb cellular structure as well as crumb sensorial properties. Crumb hardness, adhesiveness, springiness, gumminess, chewiness, and cohesiveness are named as the most commonly considered texture parameters of leavened baked products. The force required for biting the crumb samples is identified as the crumb hardness that can be measured from the peak force on the first compression given in texture profile analysis (Rathnayake et al., 2018). According to the results in Table 2, crumb hardness was increased due to the pressure application in sample P1, P2, and P3 comparatively to the unpressurized sample (C). But the hardness obtained for the product P2 is not significantly different ($p \geq .05$) to the sample C. Moreover, sample P2 has the highest springiness from all the four samples (even though crumb springiness of P2

**TABLE 2** Quality characterization of crumb samples prepared at different pressure conditions

| | P1[a] | P2[a] | P3[a] | C[a] |
|---|---|---|---|---|
| Volume ($cm^3$) | $29.362^{bc} \pm 0.954$ | $31.244^{a} \pm 0.702$ | $29.991^{b} \pm 1.009$ | $28.592^{c} \pm 0.825$ |
| Specific volume ($cm^3/g$) | $1.603^{b} \pm 0.073$ | $1.682^{a} \pm 0.031$ | $1.616^{b} \pm 0.074$ | $1.520^{c} \pm 0.039$ |
| Crumb bulk density ($g/cm^3$) | $0.625^{b} \pm 0.029$ | $0.595^{c} \pm 0.011$ | $0.620^{b} \pm 0.029$ | $0.659^{a} \pm 0.017$ |
| Crumb pH | $5.663^{c} \pm 0.0112$ | $5.824^{b} \pm 0.0451$ | $6.099^{a} \pm 0.031$ | $5.623^{c} \pm 0.058$ |
| TPA | | | | |
| Hardness (g) | $1{,}820.400^{b} \pm 180.900$ | $1{,}799.600^{bc} \pm 186.800$ | $2{,}157.000^{a} \pm 235.600$ | $1{,}547.700^{c} \pm 63.000$ |
| Springiness (mm) | $9.525^{ab} \pm 0.314$ | $9.832^{a} \pm 0.525$ | $9.213^{bc} \pm 0.501$ | $8.874^{c} \pm 0.337$ |
| Cohesiveness | $0.448^{b} \pm 0.038$ | $0.492^{a} \pm 0.044$ | $0.457^{b} \pm 0.040$ | $0.465^{ab} \pm 0.027$ |
| Gumminess (g) | $828.000^{b} \pm 151.700$ | $878.300^{ab} \pm 115.000$ | $1{,}003.400^{a} \pm 165.300$ | $656.800^{c} \pm 65.800$ |
| Chewiness (mJ) | $77.340^{ab} \pm 14.650$ | $84.750^{ab} \pm 12.110$ | $90.960^{a} \pm 18.680$ | $71.490^{b} \pm 19.150$ |

Abbreviation: TPA, texture profile analysis.

[a,b,c]Values in the same row with different superscripts are significantly different at .05 significant level.

[a]Pressurized conditions of the four samples in the chamber: P1 = sample pressurized by leavened gas itself, P2 = application of 1 $kg/cm^2$ initial pressure before fermentation, P3 = application of 1.5 $kg/cm^2$ initial pressure before fermentation, C = Control sample prepared without pressure application.

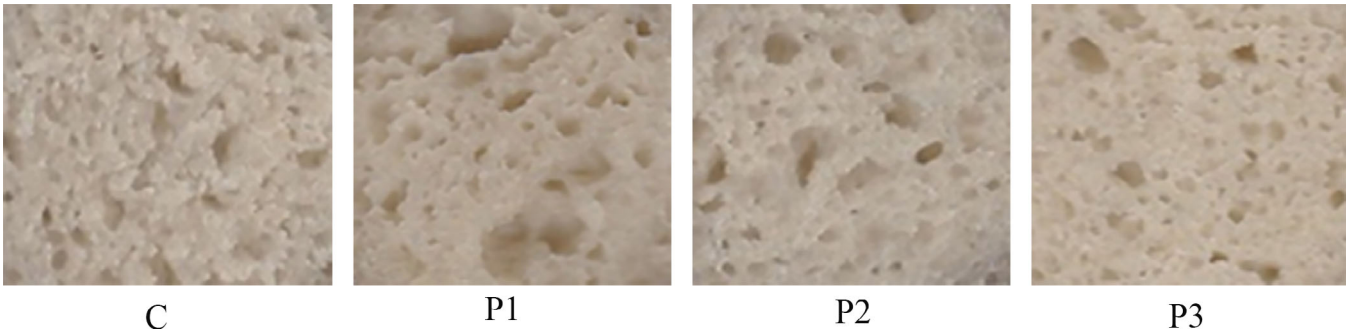


**FIGURE 2** Four crumb samples prepared under four pressure conditions: P1 = sample pressurized by leavened gas itself, P2 = application of 1 $kg/cm^2$ initial pressure before fermentation, P3 = application of 1.5 $kg/cm^2$ initial pressure before fermentation, C = control sample prepared without pressure application

**TABLE 3** Crumb cellular properties of the four samples prepared at different pressure conditions

| Crumb cellular properties | P1[a] | P2[a] | P3[a] | C[a] |
|---|---|---|---|---|
| Cell density(cellcm$^{-2}$) | 27.955$^{b}$ ± 5.770 | 31.990$^{a}$ ± 7.810 | 34.451$^{a}$ ± 4.552 | 28.592$^{b}$ ± 4.289 |
| Porosity (%) | 29.989$^{ab}$ ± 1.161 | 28.565$^{b}$ ± 3.875 | 28.187$^{b}$ ± 1.234 | 30.459$^{a}$ ± 3.714 |
| ACA (cm$^2$) | 0.0111$^{a}$ ± 0.002 | 0.0094$^{b}$ ± 0.002 | 0.0086$^{b}$ ± 0.001 | 0.0112$^{a}$ ± 0.003 |
| Cell circularity | 0.519$^{a}$ ± 0.034 | 0.529$^{a}$ ± 0.050 | 0.516$^{a}$ ± 0.032 | 0.456$^{b}$ ± 0.044 |
| Solidity | 0.731$^{a}$ ± 0.018 | 0.735$^{a}$ ± 0.025 | 0.716$^{b}$ ± 0.018 | 0.696$^{c}$ ± 0.026 |
| FD | 1.660$^{a}$ ± 0.034 | 1.633$^{b}$ ± 0.040 | 1.668$^{a}$ ± 0.022 | 1.671$^{a}$ ± 0.039 |

Abbreviations: ACA, average cell area; FD, fractal dimension.
[a,b,c]Values in the same row with different superscripts are significantly different at .05 significant level.
[a]Pressurized conditions of the four samples in the chamber: P1 = sample pressurized by leavened gas itself, P2 = application of 1 kg/cm$^2$ initial pressure before fermentation, P3 = application of 1.5 kg/cm$^2$ initial pressure before fermentation, C = Control sample prepared without pressure application.

is not significantly higher ($p \geq .05$) than P1, the value is significantly higher ($p \leq .05$) than the sample P3 and C). This represents that the sample P2 has the highest elastic recovery after removing the compressive force (Singh, Jha, Chaudhary, & Upadhyay, 2014).

When a product is biting completely, the extent of deformation apply on a food sample before it get ruptured has been named as the cohesiveness in texture profile analysis (Lawless & Heymann, 2010). Further, literature states that if higher the cohesiveness, higher the product specific volume and softer the texture. As per the results in Table 2, cohesiveness of sample P2 is significantly higher ($p \leq .05$) than P1 and P3 proving the higher specific volume and lower hardness in P2 compared to P1 and P3. Gumminess of the crumb has increased in the pressurized samples (P1, P2, and P3) significantly ($p \leq .05$) compared to the unpressurized sample (sample C) representing that the pressurized samples having of higher crumb density that persists throughout chewing (Švec & Hrušková, 2004). Even though there is not a significant different ($p \geq .05$) of the chewiness between P1, P2, and C, the chewiness of the pressurized samples (P1, P2, and P3) is higher than that of the unpressurized sample (C) which described that the pressurized samples require more energy to chew until it become suitable for swallowing as well as it represents the crumb rubbery texture during chewing (Singh et al., 2014; Švec & Hrušková, 2004).

Cell density (also named as crumb fineness) can be evaluated by the total number of cells detected over the total measured area (Che Pa, Chin, Yusof, & Abdul Aziz, 2013). According to Table 3, sample P2 and P3 had significantly higher cell density. This proves the finer crumb structure (Che Pa et al., 2013) in sample P2 and P3 compared to the sample P1 and C. Crumb porosity (void fraction) is defined as the mean value of the total cell to the total area on each slice within a considered volume. If higher the porosity, the number of larger cells (>1 mm diameter) is higher and the degree of cell uniformity is lower (Che Pa et al., 2013). Results given in Table 3 agree with this phenomena by having the highest porosity as well as the highest ACA in sample C that is significantly higher ($p \leq .05$) than the porosity and ACA of sample P2 and P3. Cell circularity is a shape factor to analyze the cell shape. A perfect circle has a shape factor of 1, and a line has a shape factor reaching for 0 (Crowley, Grau, & Arendt, 2000). Cell circularity of sample C is significantly lower than ($p \leq .05$) the pressurized samples (P1, P2, and P3) proving that the application of pressure produces more circular and uniform pores. Crumb solidity is the ratio between crumb area and convex area. The solidity of sample P2 is significantly higher ($p \leq .05$) than P3 as well as C. But the solidity of the sample P2 is not significantly different ($p \geq .05$) from the sample P1.

Porous crumb structure has a complex mechanical behavior (Gonzales-Barron & Butler, 2008; Scanlon & Zghal, 2001). As a result of that, a close examination of different slices within a single sample also can reveal considerable variation in the cell characteristics (Gonzales-Barron & Butler, 2008). FD can provide a quantitative descriptor of the morphology of materials that have complex and irregular structures (Farrera-Rebollo et al., 2012; Pérez-Nieto et al., 2010). As declared in Table 3, sample P2 has the lowest FD that is significantly lower ($p \leq .05$) compared to the other three samples (P1, P3, C) representing that the sample P2 has more simpler and smoother gray level crumb images (Pérez-Nieto et al., 2010).

According to Miller, Graf, and Hoseney (1994), carbon dioxide dissolves in the dough phase within the early stage of fermentation (before get saturated and diffuse into the gas bubbles) and react with water to form carbonic acid resulting in the acidic pH of the dough mass. The initial pH of the dough in the current study was recorded as 6.150 ± 0.062. pH of the dough gets reduced with the progress of the fermentation process (Aplevicz, Ogliari, & Sant'Anna, 2013). Even though the pH value of the sample P2 is significantly higher ($p \leq .05$) than P1 and C (Table 2), the value is within the range of the Sri Lankan regulatory requirement of 5.3–6.0 (Navaratne, 2007).

As the pH value of the sample P3 is significantly higher than ($p \leq .05$) all the other three samples as well as not within the range of the regulatory requirement, sample P3 can be considered as not sufficiently completed the fermentation process under given fermentation conditions (1.5 kg/cm$^2$, 30 ± 1°C, 180 min) compared to the other three samples. Further, when comparing sample P2 and P3, the significantly lower volume, specific volume ($p \leq .05$), significantly higher ($p \leq .05$) bulk density, hardness (Table 2) as well as poorly developed crumb structure (Figure 2) in sample P3 proves the phenomena that the sample P3 has not sufficiently completed the fermentation process under given conditions. Hence, according to the results obtained for the current study, it proves that increasing the amount of pressure

applied prior to the fermentation and gelatinization can affect the yeast activity and retard the fermentation rate for some extent.

## 4 | CONCLUSION

Fermentation and gelatinization under pressurized conditions have improved the leavened gas retention capacity with resulting in a more stable, firm, gummy, and springy textured product compared to the unpressurized sample. According to the crumb volume, specific volume, bulk density, crumb texture parameters as well as crumb cellular structure properties, sample P2 (Application of 1 kg/cm$^2$ initial pressure before fermentation) was the best option under selected fermentation time of 180 min. Application of pressure can affect the yeast activity and hence can retard the fermentation rate for some extent. However, the time required for gelatinization was reduced in pressurized samples.

### ACKNOWLEDGMENT

The authors wish to offer their gratitude toward the National Science Foundation, Sri Lanka for funding the project and Department of Food Science and Technology, University of Sri Jayewardenepura, Sri Lanka for providing laboratory facilities.

### AUTHOR CONTRIBUTION

H.A.R. and S.N. designed the study. H.A.R. collected and analyzed the data and drafted the manuscript. S.N. provided the initial study idea, supervised the study and edited the manuscript. C.N. supervised the study and edited the manuscript.

### ETHICAL STATEMENTS

#### Conflict of Interest

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

#### Ethical Review

This study does not include any human or animal testing.

### ORCID

*Heshani A. Rathnayake* https://orcid.org/0000-0002-3086-0023

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**How to cite this article:** Rathnayake HA, Navaratne S, Navaratne C. Improving porous crumb structure of rice-related leavened food products by fermentation and gelatinization at slightly higher air pressure conditions. *J Texture Stud*. 2019;50:564–570. https://doi.org/10.1111/jtxs.12465