Improvement of cooking quality of germinated brown rice attributed to the fissures caused by microwave drying

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Abstract Germinated brown rice (GBR) contains rich bio-active components, but has poor edible quality. To improve the cooking quality of GBR, fissure generation in kernels caused by microwave drying were investigated considering cooking properties, microstructure and textural attributes. The microwave intensity had significant effects on the fissure percentage of GBR, and microwave intensity of 3–4 W/g may be suitable for the microwave drying of GBR based on the distribution of fissure percentage for the GBR. The fissures of GBR caused by microwave drying provided the suitable penetration routes of water into GBR kernel. Appropriate fissure amount in range of 3–4 in GBR kernels were conducive to increase its cooking quality and rice taste due to the moderate water absorption and starch gelatinization. The results present a new viewpoint from the perspective of fissures inside grain kernels to evaluate the drying quality of cereal materials such as GBR.

Keywords Germinated brown rice · Fissure · Microwave drying · Cooking quality · Texture properties

Introduction

Brown rice is germinated in the closed conditions with temperature of 20–30 °C and 90% relative humidity to produce germinated brown rice (GBR) with the bud length of 1.0–2.0 mm (Kim et al. 2012). GBR contains rich

nutritional and bio-functional ingredients including gamma-aminobutyric acid (GABA), amino acids and vitamins (Cornejo and Rosell 2015). Due to highly nutritional benefits, GBR and its products have received high recognition in Asian countries and wide popularity especially for the health-conscious consumers, and also frequently used as a nutritive formulation in foods (Chalermchaiwat et al. 2015).

In spite of its unique nutritional qualities, brown rice products like GBR are difficult to be widely accepted to act as suitable table rice. This is attributed to its poor cooking quality in terms of long cooking time, high hardness, less chewiness and rough taste (Wu et al. 2013). These shortcomings are resulted from the rich tough fibers of outer bran layer of GBR. The impervious compact fibrous layer prevents the penetration of water into the interior of GBR kernel, resulting in a lengthy cooking time, rough texture of the cooked rice (Zhang et al. 2015b). Cooking quality of GBR is still inferior compared to the polished rice. Although germination process may soften the outer bran layer of GBR to a certain extent (Chung et al. 2012), some efforts have been attempted to weaken the hardness of GBR surface so as to improve the cooking quality and palatability of brown rice products. Ultrasound treatment and addition of cellulase enzyme were used to destroyed the cortical structure of GBR and degrade cortical non-starch polysaccharides to produce quick-cooking brown rice with moderate hardness (Zhang et al. 2015a, b). However, moderate fissures inside GBR may be accepted due to its directly cooking other than further milling with high nutrition ingredients (Yu et al. 2017). Timely drying treatment is necessary step for the fresh GBR to a desired moisture content below 14.5% (*w.b.*) to prevent the quality deterioration from microorganisms such as bacteria and fungi (Zheng et al. 2011). Microwave drying meets the

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requirements of the drying treatment of GBR with high drying rate, low energy consumption and sterilization (Olatunde et al. 2017; Xu et al. 2017). The volumetric heating mode of microwave drying may result in significant changes in the physicochemical composition, morphology and the microstructure in food materials (Funebo et al. 2000).

The existing literatures reviewed the cooking quality of rice mainly focus on the milled rice such as polished rice. Little information was published about the effects of fissures in rice kernels on its cooking quality. Hence, it is essential to investigate the influences of fissures on cooking quality of GBR. The specific objectives of current study were as follows:

1. To investigate the distribution of fissured GBR kernels caused by microwave drying;
2. To analyze the effects of fissures on cooking quality of GBR;
3. To explain the change in cooking quality of GBR attributed to the fissures caused by microwave drying.

Materials and methods

Preparation of GBR material

Fresh GBR was provided by Jindu rice processing industry Co., Ltd. (Harbin, China) from the local variety of long-grain. These samples were stored in a refrigerating cabinet (SC/SD-332, Haier Inc., Qingdao, China) with cooling temperature of 4–5 °C. The cooled samples were taken out to reach room temperature (20 ± 2 °C) for the experiments of microwave drying.

Microwave drying experiments of fresh GBR

The moisture content of GBR was determined according to the standard method (AOAC 2005). The initial moisture content of GBR was 35.94 ± 0.60 (% *w.b.*). The weight of GBR was 200 ± 0.01 g for all test runs. Each GBR sample was spread on a glass disc with thin layer. The glass disc loading GBR samples was placed in a microwave workstation (MWS, FISO Technologies Inc., Quebec, Canada) with a frequency of 2450 MHz. The drying experiments were performed under the microwave intensities from 1 to 5 W/g. According to preliminary experiments, the drying time to achieve the desired moisture content of 13.0–14.5% (*w.b.*) for GBR with the same initial moisture content were 36, 12, 8, 6, 5 min at microwave intensity of 1, 2, 3, 4 and 5 W/g, respectively. The final moisture content of GBR after microwave drying experiments was in range of 13.34–14.19% (*w.b.*). Each set of parameters of microwave

intensity was done in triplicate and average value was reported.

Determination of fissures in MDGBR kernels

The microwave-dried GBR (MDGBR) kernels were firstly sealed in polyethylene bags then stored at room temperature for 72 h. One hundred kernels were randomly collected from the stored MDGBR samples for the inspection of fissure amount on a white translucent plate with a fluorescent bulb (Duangkhamchan and Siriamornpun 2015). Three replicates were performed for each measurement. The fissures inside GBR kernels were observed and recorded by naked eye, with fissure amount of 0, 1, 2, 3, 4 and more than 5 fissures. The fissures state of GBR kernels were presented as F0, F1, F2, F3, F4 for 0, 1, 2, 3 and 4 fissure amount, respectively. For the kernels with fissure amount more than 5, it was difficult to accurately determine the fissure amount due to severe fissure degree, thus these kernels were all classified as F5. The fissure morphology and classification of MDGBR kernels is shown in Fig. 1. The fissure percentage was introduced to quantify the proportion of MDGBR kernels with fissure degree shown in Eq. (1).

$$\text{Fissure percentage (\%)} = \frac{N_f}{N_t} \times 100 \quad (1)$$

where N_f is the total amount of kernels at certain fissure degree (0, 1, 2, 3, 4, ≥ 5); N_t is the total amount of the randomly selected MDGBR kernels ($N_t = 100$).

Investigation of cooking quality of GBR

The cooking properties, texture characteristics and microstructure changes were used to investigate the effects of fissures on cooking quality of dried GBR (DGBR), and a research route to evaluate the cooking quality of GBR is shown in Fig. 2. To differentiate and analyze the effects of fissure degree on the cooking properties of MDGBR, the MDGBR kernels were divided into three categories (without fissures, with single fissures and with multi-mixed fissures), and named as F0–FA from left to right (Fig. 2), respectively. For these categories of GBR fissures, the multi-mixed fissures represented the mixture from single type fissures (F1–F4), such as the F12 represented the kernel mixture of F1 and F2, and the F34 represented the kernel mixture of F3 and F4. FA represented the unclassified MDGBR kernels consisting of F0, F1, F2, F3, F4 and F5. Considering real MDGBR consisting of various fissure degree of kernels, the multi-mixed fissure kernels from the random combination of F5, F12, F34 and FA were used to investigate its effects on the cooking quality of GBR. To evaluate the effects of drying intensity on the fissure

(a) Fissure morphology of MDGBR kernels

(b) Classification of MDGBR kernels

Fig. 1 Fissure morphology and classification of MDGBR kernels. MDGBR denote the microwave-dried GBR, and it was distinguished on the basis of the amount of fissures in kernels, namely (1) 0 fissure

(F0), (2) 1 fissure (F1), (3) 2 fissures (F2), (4) 3 fissures (F3), (5) 4 fissures (F4), (6) more than 5 fissures (F5). The classification of MDGBR kernels was based on the fissure amount in kernels

generation of GBR, the fresh GBR dried by a comparatively shade drying was employed as shade-dried GBR (SDGBR) in natural air convection of room temperature. The SDGBR as control samples (named R) are shown in

Fig. 2. The cooked DGBR (CGBR) were further used to conduct the texture analysis by using texture profile analysis (TPA) method and microstructure analysis by scanning electron microscope (SEM), respectively.

Fig. 2 Research route to evaluate cooking quality of DGBR. DGBR denotes the dried GBR, including the MDGBR dried by microwave drying and the SDGBR dried by shade drying. R denotes the SDGBR kernels without fissures. CGBR denotes the cooked DGBR. F0–F4 denote the MDGBR kernels with the fissure amount of 0, 1, 2, 3 and 4, respectively. F5 denotes the multi-mixed MDGBR kernels with the

fissure amount of more than 5. The multi-mixed fissures represent the mixture from single type fissures (F1–F4), such as the F12 represents the kernel mixture of F1 and F2, and the F34 represents the kernel mixture of F3 and F4. FA represents the unclassified MDGBR kernels consisting of F0, F1, F2, F3, F4 and F5

Cooking experiments of DGBR

The optimum cooking time, water uptake ratio, volume expansion ratio and total solids loss were introduced to evaluate the cooking properties of DGBR.

Optimum cooking time The optimum cooking time was determined for each sample by the glass plate white center method (Wu et al. 2016). About 10 g DGBR samples were added to 70 ml of boiling water ($98 \pm 1^\circ\text{C}$) in a 250 ml beaker placed on a hot plate. After boiling for 10 min, three replicates of 10 kernels were withdrawn every minute and then pressed down between two glass plates. The cooked DGBR indicated no uncooked center by means of pressed grains. The cooking duration achieving cooked status was recorded as the optimum cooking time. An average value of three independent determinations was reported.

Other parameters of cooking properties, including water uptake ratio, volume expansion ratio and total solids loss were based on the optimum cooking time.

Water uptake ratio DGBR kernels of 5 g were put in distilled water of 50 ml in an aluminum container, then cooked it in a boiling water bath until the optimum cooking time determined previously. The superficial water of cooked DGBR samples was removed by using filter paper and then accurately weighed it. The water uptake ratio was defined as the mass ratio of dried samples before and after cooking (Singh et al. 2005).

$$\text{Water uptake ratio} = \frac{m_f - m_i}{m_i} \quad (2)$$

where m_i is the initial mass of DGBR samples (g), m_f is the final mass of DGBR samples (g).

Volume expansion ratio According to the above-mentioned cooking methods in section “Water uptake ratio”,

the volumes of DGBR samples before and after cooking were calculated by using the volume displacement method (Wu et al. 2016). The volume expansion ratio was expressed as the volume ratio of cooked samples to that of their uncooked counterparts.

$$\text{Volume expansion ratio} = \frac{V_f - V_i}{V_i} \quad (3)$$

where V_i is the initial volume of DGBR samples (cm^3), V_f is the final volume of DGBR samples (cm^3).

Total solids loss The total solids loss of cooked DGBR was determined by modifying a method described by Gujral and Kumar (2003). According to the cooking method in section “Water uptake ratio”, the cooked kernels were removed by using a filter sieve with aperture of 1.2 mm, then the residual liquid was evaporated at 105 °C to constant weight. The resultant dry matter was weighed to calculate the total solids loss.

$$\text{Total solids loss}(\%) = \frac{W_f}{m_i} \times 100 \quad (4)$$

where m_i is the initial mass of DGBR samples (g), W_f is the mass of dry matter in residual liquid of cooked DGBR samples (g).

Texture testing of CGBR

Preparation of CGBR The preparation route of CGBR samples was as follow: (1) the classified DGBR kernels (F0–FA and R) of 10 g were firstly put in the aluminum container with a ratio of 1:1.4 g/ml for rice and distilled water, (2) then five aluminum containers loading DGBR samples were all placed in an electric rice cooker (SR-G15C1-K type, Panasonic Kitchen Electrical Appliances Co. Ltd., Hangzhou, China). To avoid the effects of pre-washing on the texture, the samples were directly soaked for 20 min before cooking. The cooking process of DGBR was automatically completed in the cooker and then kept warm for 30 min (Hapsari et al. 2016). Finally, the CGBR samples were placed in a closed container and cooled to room temperature for the subsequent texture testing.

Textural profile analysis of CGBR According to the test methods of textural profile of cooked rice (Huang et al. 2014) with an appropriate modification, the textural properties of CGBR samples were determined by using a texture analyzer (Stable Micro System Ltd., TA.XT Plus, Surrey, UK). The CGBR samples with 50 mm diameter and 15 mm height were prepared by using an aluminum container. A standard TPA program with a successive two-cycle compression was employed to conduct the texture testing. A cylindrical probe P/50 with 50 mm diameter was

used to compress the samples to 75% deformation with the time interval of 5 s at a pre-test speed of 1 mm/s, test speed of 0.5 mm/s and post-test speed of 0.5 mm/s. The texture testing was repeated 5 times for each treatment. The textural parameters including hardness, adhesiveness, springiness, cohesiveness, stickiness and chewiness, were recorded according to TPA curve attributes (Zheng et al. 2011).

Microstructure analysis of DGBR and CGBR

The histological characters of DGBR and CGBR were observed by using SEM (Quanta-200, FEI Company, Netherlands). The CGBR kernels were lyophilized by using a freezing-vacuum dryer (TD-50, Shanghai Pudong freeze dryer equipment Co., Ltd., Shanghai, China) to maintain the structure of the samples. To observe the microstructure of samples, the kernels were fractured at the center along the cross-section by using a razor blade. With the surface fractured or striped upward, the samples were mounted on an aluminum stub by using double-sided stick tape and coated with a thin film of gold, then examined with the magnification of 300×, 1000× and 3000× at an accelerating voltage of 12.5 kV. Finally, the microstructure of the samples was observed along the cross-section at the center.

Data analysis

The data were expressed by mean $\pm$ standard deviation (SD). The data were analyzed by analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) test, which were performed by using SPSS statistics software (Version 19.0, SPSS Inc., Chicago, IL, USA). Statistical significance for differences was tested at 5% probability level ($p < 0.05$). The data was plotted by Origin software (Version 9.0, OriginLab Corp., Massachusetts, USA).

Results and discussion

Distribution of fissured GBR kernels under microwave drying

Figure 3 shows the distribution of fissure percentage for the MDGBR kernels under microwave intensity of 1–5 W/g. Overall, the microwave intensity had significant effects on the fissure percentage of MDGBR ($p < 0.05$). The fissure percentage of F0 (no fissure) was 15.00% at microwave intensity of 1 W/g, while it was 4.33% at microwave intensity of 5 W/g. The higher microwave intensity caused lower fissure percentage of F0. This was attributed to the

Fig. 3 Distribution of fissure percentage for MDGBR kernels under microwave intensity of 1–5 W/g. Data were expressed as mean $\pm$ SD of triplicates determinations ($n = 3$), and the same letters indicated that there were no significant differences ($p > 0.05$) for the same evaluation index under different microwave intensity of 1–5 W/g. MDGBR denotes the microwave-dried GBR, and the F0–F5 denote MDGBR kernels with the fissure amount of 0, 1, 2, 3, 4, and more than 5, respectively

high microwave intensity inducing great moisture gradient inside MDGBR kernel to increase its fissure degree (Khraisheh et al. 2004). Thus, it resulted in a decrease of the F0 of MDGBR. In terms of the F1, the fissure percentage of MDGBR were 18.67%, 15.00%, 12.67%, 9.67% and 7.67% under microwave intensity of 1–5 W/g, respectively. No significant difference was found between F1 and F0 of MDGBR. However, the fissure percentage of F2 increased from 24.00 to 25.67% under separate experiments of microwave intensity of 1 and 2 W/g. This was resulted from the evolution of F0 and F1 into the F2 under microwave intensity of 2 W/g. Then, it decreased to 18.00% at microwave intensity of 5 W/g. Similarly, the fissure percentage of F3 initially increased from 28.00 to 34.67% with the microwave intensity from 1 to 3 W/g, and then reduced to 30.00% at microwave intensity of 5 W/g. The fissure percentage for F4 rose from 9.00 to 24.33% and for F5 from 5.33 to 15.67%, while both did not significantly change under the microwave intensity lower than 2 W/g ($p > 0.05$). According to the fissure percentage of 15.00% for MDGBR (Fig. 3), the domination of fissure type and total percentage were obtained as F0–F3 (F0, F1, F2 and F3) with 85.67%, F1–F3 (F1, F2 and F3) with 71.67%, F2–F3 (F2 and F3) with 57.34%, F2–F4 (F2, F3 and F4) with 72.33%, and F2–F5 (F2, F3, F4 and F5) with 88.00% at microwave intensity of 1, 2, 3, 4 and 5 W/g, respectively. These results indicated that 4–5 fissures in MDGBR kernels were dominant in the later stage of drying under microwave intensity higher than 4 W/g. However, severe fissures easily caused the undesired drying quality of MDGBR, such as burnt appearance and degradation of nutrient composition (Zheng et al. 2011). Therefore, an appropriate microwave intensity of 3–4 W/g may be

suitable for the microwave drying of GBR considering the drying efficiency and quality.

Effects of fissures on cooking quality of GBR

Analysis of cooking properties of DGBR

The effects of fissure degree on the cooking properties of DGBR based on the cooking indexes including optimum cooking time, water uptake ratio, volume expansion ratio and total solids loss are shown in Fig. 4.

Optimum cooking time As illustrated in Fig. 4a, the optimum cooking time of MDGBR (F0) was significantly lower than that of SDGBR (R) ($p < 0.05$). The fissure degree (F0–FA) had significant effects on the optimum cooking time of MDGBR ($p < 0.05$). The drying time for single fissure (F0–F4) and multi-mixed fissures (F5–FA) significantly decreased with the increase of fissure degree ($p < 0.05$). The fissure inside MDGBR provided the route of moisture absorption into the interior during cooking (Fig. 4b) to promote the gelatinization of starch and further to reduce the cooking time. And the shortest optimum cooking time for the single fissure and the multi-mixed fissure kernels were the F4 (19.90 ± 0.40 min) and the F5 (18.70 ± 0.47 min), respectively. The severe fissure F5 easily caused the cracked kernels during cooking to reduce the palatability of cooked DGBR. Considering the cooking time and final taste quality of cooked rice, the F34 (20.84 ± 0.67 min) may be better suited to act as the optimum cooking time for the multi-mixed fissure kernels than that of F5. The optimum cooking time for MDGBR with F34 was only 2.14 min higher than that with F5, but it

Fig. 4 Effects of fissure degree on the cooking properties of DGBR. Data were expressed as mean $\pm$ SD of triplicates determinations ($n = 3$), and the same letters indicated that there were no significant differences ($p > 0.05$). DGBR denotes the dried GBR, including the MDGBR dried by microwave drying and the SDGBR dried by shade drying. R denotes the SDGBR kernels without fissures. F0–F4 denote the MDGBR kernels with the fissure amount of 0, 1, 2, 3 and 4,

respectively. F5 denote the multi-mixed MDGBR kernels with the fissure amount of more than 5. The multi-mixed fissures represented the mixture from single type fissures (F1–F4), such as the F12 represented the kernel mixture of F1 and F2, and the F34 represented the kernel mixture of F3 and F4. FA represented the unclassified MDGBR kernels consisting of F0, F1, F2, F3, F4 and F5

may be acceptable for consumers considering taste quality of cooked rice.

Water uptake ratio Comparing R and F0 in Fig. 4b, it can be seen that the water uptake ratio of SDGBR and MDGBR were 1.95 ± 0.06 and 2.16 ± 0.05 , respectively, which indicated that the microwave drying enhanced moisture absorption related to the microstructure of MDGBR. The water uptake ratio of MDGBR significantly increased from 2.16 ± 0.05 to 2.65 ± 0.02 ($p < 0.05$) compared from F0 to F3 in Fig. 4b, and then decreased to 2.57 ± 0.03 from F3 to F4. The reduction of water absorption at higher fissure degree resulted from the rearrangement of starch

granules inside sample (Inprasit and Noomhorm 2001). The water uptake ratio of cooked rice was positively related to the absorption of water during cooking (Pal et al. 2016). The formation of starch-lipid complexes, interaction between amylose and amylopectin, and the weak hydroxyl hydration of starch weakened the water uptake ratio of starch for MDGBR (Derycke et al. 2005). The highest water uptake ratio for the single fissure and the multi-mixed fissure were the F3 (2.65 ± 0.02) and F34 (2.53 ± 0.03), respectively.

Volume expansion ratio Comparing R and F0 in Fig. 4c, the volume expansion ratio of SDGBR and MDGBR were

2.87 ± 0.03 and 3.06 ± 0.05 , respectively, which revealed that microwave drying may promote water absorption and further to result in starch swell inside MDGBR. As shown in Fig. 4c, the volume expansion ratio of MDGBR significantly increased from 3.06 ± 0.05 to 3.60 ± 0.04 with fissure degree from F0 to F3 ($p < 0.05$), and then decreased to 3.49 ± 0.03 with the fissure degree from F3 to F4. Increase of fissures in kernels promoted the expansion of rice kernels resulting from high water absorption. However, for the severe fissure degree, the formation of starch-lipid complexes resulted in the decrease of water uptake ratio, which led to the decrease of volume expansion ratio. Besides, the multi-mixed fissures (F5–FA) also failed to affect the volume expansion ratio of MDGBR. And the highest volume expansion ratio for the single fissure and the multi-mixed fissure were the F3 (3.60 ± 0.04) and F34 (3.47 ± 0.06), respectively.

Total solids loss Comparing R and F0 in Fig. 4d, the total solids loss of SDGBR and MDGBR were $7.93 \pm 0.10\%$ and $8.49 \pm 0.08\%$, respectively, which showed that the bran layer of GBR prevented the solids from diffusion toward the exterior of GBR. However, the high cooking loss was undesirable because it represented high solubility of grains constituents and low cooking tolerance resulting in sticky texture (Pal et al. 2016). Results from the F0 to F4 in Fig. 4d demonstrated that the total solids loss of MDGBR significantly increased from $8.49 \pm 0.08\%$ to $10.30 \pm 0.30\%$ ($p < 0.05$). This was due to the great disruption of the outer bran layer which easily facilitated the leaching of solids into the surrounding water during cooking (Pal et al. 2016). The total solids loss of MDGBR increased with its fissure degree. For the severe fissures of MDGBR, the interaction between the starch and protein limited the leaching of solids during cooking (Duangkhamchan et al. 2017). Similarly, the multi-mixed fissures (F5–FA) also had no largely significant effects on the total solids loss of MDGBR.

In fact, the GBR kernels undergoing microwave drying were usually in mixture kernels with different amount of fissures. The multi-mixed fissure kernels were the actual dried status for the microwave drying of GBR. Consequently, the suitable fissure ranges in GBR kernels should be selected from the multi-mixed fissures (F5–FA) kernels with respect to a lowest cooking time and total solids loss, highest water uptake ratio and volume expansion ratio. Comparing the cooking properties among the multi-mixed fissure kernels of F5, F12, F34 and FA, the water uptake ratio and volume expansion ratio were the highest for F34. Despite the total solids loss of MDGBR with F34 was higher than that of F12, no significant changes of total solids loss from the F5 to FA were found ($p > 0.05$). The optimum cooking time of MDGBR was determined as F34

based on the analysis of section “Optimum cooking time”. Therefore, the 3–4 fissures (F34) may be the optimal fissure range in GBR kernels suitable for microwave drying.

Analysis of textural properties of CGBR

Figure 5 shows the changes of textural properties of CGBR in terms of the hardness, adhesiveness, springiness, cohesiveness, stickiness and chewiness.

Hardness Comparing R and F0 in Fig. 5a, the hardness of cooked SDGBR and MDGBR were 142.45 ± 3.15 N and 126.57 ± 2.86 N, respectively, which showed that the cooked MDGBR had low hardness. The fissures inside MDGBR kernel reduced the binding strength of kernel structure and promoted the water absorption during cooking to result in full gelatinization of starch to cause low hardness of cooked MDGBR. The individual contributions from F0 to F3 for single fissure on the hardness of cooked MDGBR were presented in Fig. 5a, the hardness significantly decreased from 126.57 ± 2.86 N to 102.91 ± 1.24 N ($p < 0.05$), and then increased to 110.51 ± 1.76 N with fissure degree from F3 to F4. The changes of hardness of cooked MDGBR influenced by the multi-mixed fissures (F5–FA) were lower than that caused by its single fissures (F0–F4). The lowest hardness of cooked MDGBR for F34 indicated that the mixed MDGBR with different proportions of fissures can decrease its hardness and increase taste to some extent. The starch gelatinization of MDGBR kernels with multi-mixed fissures may maintain a suitable hardness of cooked MDGBR than those of single fissures.

Adhesiveness Comparing R and F0 in Fig. 5b, the adhesiveness of cooked SDGBR and MDGBR were 14.49 ± 0.61 N.s and 16.86 ± 0.45 N.s, respectively, which showed that the adhesiveness of cooked MDGBR increased by microwave drying treatments. From the F0 to F3 in Fig. 5b, the adhesiveness of cooked MDGBR significantly increased from 16.86 ± 0.45 N.s to 20.98 ± 0.44 N.s ($p < 0.05$), and then decreased to 17.73 ± 0.34 N.s with the fissure degree from F3 to F4. The multi-mixed fissures (F5–FA) had significant effects on the adhesiveness of cooked MDGBR ($p < 0.05$) in Fig. 5b. The results of high adhesiveness for the F12 or F34 indicated that the mixed fissures of MDGBR may increase its adhesiveness. Starch loss of cooked MDGBR from the effusion of fissures increased with the fissure degree, which resulted in a decrease of its internal viscosity (Wu et al. 2016). The starch gelatinization of MDGBR kernels with multi-mixed fissures enhanced adhesiveness texture of cooked MDGBR than those of single fissures. These results were in good agreement with the findings that the

Fig. 5 Effects of fissure degree on the textural properties of CGBR. Data were expressed as mean $\pm$ SD of five determinations ($n = 5$), and the same letters indicated that there were no significant differences ($p > 0.05$). The negative sign for the values of the

adhesiveness (b) and the stickiness (e) only represent the direction of force in TPA curves, thus only the size of the value were analyzed without consideration of the negative sign in section “Adhesiveness” and “Stickiness”

adhesiveness was related to the amount of starch and starch gelatinization (Hapsari et al. 2016). The hardness and adhesiveness had negative correlation due to apparent amylose content (Singh et al. 2014). The increase of the adhesiveness of cooked MDGBR may be attributed to the reduction of its hardness. The effects of fissure amount of MDGBR on its hardness of cooked rice were analyzed in section “Hardness”.

Springiness Comparing R and F0 in Fig. 5c, the springiness of cooked SDGBR and MDGBR were 0.48 ± 0.01 and 0.50 ± 0.01 , respectively, which clearly indicated the increase of springiness of cooked MDGBR. It can be seen from the F0 to F3 in Fig. 5c, the springiness of cooked MDGBR increased from 0.50 ± 0.01 to 0.61 ± 0.01 ($p < 0.05$), and then decreased to 0.57 ± 0.02 with the fissure degree from F3 to F4. This resulted from the bran layer of GBR was destroyed and softened by microwave drying (Hapsari et al. 2016). The changes of springiness for cooked MDGBR had negative trends as compared to its hardness. Enough starch gelatinization and accumulation of MDGBR kernels during cooking contributed to the increase of springiness of cooked MDGBR with fissure degree from F0 to F3. However, starch loss and thermal decomposition of macromolecular substance (Ramesh et al. 1999) increased at the fissure degree of F3 and F4, which reduced the springiness of cooked MDGBR. No significant effects ($p > 0.05$) of the multi-mixed fissures (F5–FA) on the springiness of cooked MDGBR was found.

Cohesiveness Comparing R and F0 in Fig. 5d, the cohesiveness of cooked SDGBR and MDGBR were 0.13 ± 0.01 and 0.15 ± 0.01 , which demonstrated that microwave drying increased the cohesiveness of cooked MDGBR. From F0 to F3 in Fig. 5d, it can be seen that the cohesiveness of cooked MDGBR significantly increased from 0.15 ± 0.01 to 0.20 ± 0.01 ($p < 0.05$), and then decreased to 0.19 ± 0.01 with the fissure degree from F3 to F4. Increase of cohesiveness of cooked MDGBR was due to the strength of the intermolecular forces inside rice kernels caused by partial retrogradation of cooling starch (Derycke et al. 2005). Therefore, the reduction of cohesiveness of cooked MDGBR was attributed to the starch loss and thermal decomposition of macromolecular components with increase of fissure degree (Ramesh et al. 1999). Likewise, the multi-mixed fissures (F5–FA) had no significant effects ($p > 0.05$) on the cohesiveness of cooked MDGBR. The high cohesiveness for the F34 indicated that the cohesiveness of cooked MDGBR increased with different proportions of fissures.

Fig. 6 Microstructure of DGBR and CGBR. AG aleurone grain, SG starch gelatinization, SSG small starch granule, LSG large starch granule, CSG compound starch granule, CW cell walls, SM starch melting, SLC starch-lipid complexes

Stickiness Comparing R and F0 in Fig. 5e, the stickiness of cooked SDGBR and MDGBR were 3.86 ± 0.13 and 4.20 ± 0.15 , respectively, which indicated the increase of stickiness of cooked MDGBR. The stickiness of cooked rice was influenced by the protein oryzenin, which may be interacted by starch gelatinization during cooking of rice grain (Pal et al. 2016). From F0 to F4 in Fig. 5e, it can be seen that the stickiness of cooked MDGBR significantly increased from 4.20 ± 0.15 to 5.41 ± 0.13 ($p < 0.05$). This was mainly attributed to the leaching of starch and protein in GBR, which effused from the fissures during cooking to increase the viscosity of CGBR (Li and Gilbert 2018). No significant effects ($p > 0.05$) of the multi-mixed fissures (F5–FA) on the stickiness of cooked MDGBR was found, but the MDGBR with F34 had the high stickiness of cooked MDGBR. This indicated that the MDGBR with multi-mixed fissures may increase the stickiness of cooked MDGBR.

Chewiness Comparing R and F0 in Fig. 5f, the chewiness of cooked SDGBR and MDGBR were 9.07 ± 0.56 and 9.63 ± 0.25 , respectively, which indicated the increase of chewiness of cooked MDGBR. From F0 to F3 in Fig. 5f, it can be seen that the chewiness of cooked MDGBR significantly increased from 9.67 ± 0.25 to 12.51 ± 0.80 ($p < 0.05$), and then increased to 11.86 ± 1.38 with the fissure degree from F3 to F4. According to the mathematical description as $\text{Chewiness} = \text{Hardness} \times \text{Cohesiveness} \times \text{Springiness}$, the changes of chewiness depended on the cohesiveness and springiness with the increasing followed by a decreasing trends with the increase of fissure degree. Therefore, the reason resulting in the changes of chewiness of cooked MDGBR was the similar as that of the cohesiveness and springiness.

In summary, an appropriate textural indexes for CGBR should be also selected from the multi-mixed fissures (F5–FA) kernels with respect to a low hardness and high adhesiveness, springiness, cohesiveness, stickiness and chewiness associating with the cooking properties of DGBR. Therefore, the F34 may be the optimal fissure ranges for highly cooking quality of CGBR kernels.

Explanation of the change in cooking quality of GBR attributed to the fissures caused by microwave drying

Figure 6 shows that the effects of fissure degree (R–F5) on the microstructures of DGBR including SDGBR

(Fig. 6A1–A3) and MDGBR (Fig. 6B1–G3), and the corresponding CGBR cooked by the SDGBR (Fig. 6a) and the MDGBR (Fig. 6b–g).

Comparing the microstructure of SDGBR (A1–A3 in Fig. 6) and MDGBR (B1–B3 in Fig. 6), it can be seen that the SDGBR had obviously compact internal structure with a regular arrangement of starch granules of MDGBR. This result indicated that the shade drying as moderate drying mode at low drying rate had un-significant effect on the structure of starch granules and texture properties of rice kernels (Inprasit and Noomhorm 2001). The compact arrangement of starch granules of MDGBR was disrupted to form fissures or voids due to the intense diffusion of moisture within GBR under the microwave drying (Balbinoti et al. 2018; Rewthong et al. 2011).

The internal microstructure of MDGBR under the magnification of $300\times$ ($100\ \mu\text{m}$), $1000\times$ ($20\ \mu\text{m}$) and $3000\times$ ($10\ \mu\text{m}$) were presented to assess the individual contributions of fissure on the internal structure of MDGBR. The fissures have obvious differences on the internal microstructure of MDGBR according to the SEM images from B1 to G1 under the magnification of $300\times$ in Fig. 6, and severe fissures appeared with the fissure degree. From the B2 to G2 under the magnification of $1000\times$ in Fig. 6, the obvious changes of starch structure of MDGBR with appearance of micro-pores in the internal structure with the fissure degree. Moreover, the starch granules gradually formed the compound starch granules (CSG) with increase of fissure degree observed from B3 to G3 under the magnification of $3000\times$ in Fig. 6, and even partial starch gelatinization occurred (Fig. 6G3). This may be attributed to the gelatinization of starch granules inside MDGBR kernels. The high initial moisture content of GBR and rising temperature during microwave drying, resulted in the appearance of micro-pores and starch melting in the interior of MDGBR (Huang et al. 2014). The internal microstructure of cooked SDGBR (Fig. 6a) was in compact arrangement, which easily lead to a great hardness of cooked rice, while the looser microstructure of cooked MDGBR (Fig. 6b) caused by starch gelatinization than those of SDGBR. Compared with the SEM images from b to g in Fig. 6, the gelatinization degree of starch increased with the fissure degree of MDGBR. However, the absorption and diffusion of water inside MDGBR in the subsequent cooking process may be hindered due to the formation of starch-lipid complexes to reduce the cooking quality of MDGBR (Tan et al. 2018). The observation of micro-structure of SDGBR and MDGBR from SEM verified the fissures of GBR in range of 3–4 caused by microwave drying provided the suitable penetration route of water into GBR kernel to promote its cooking quality.

Conclusion

Superiority of microwave drying for fresh GBR processing emerges as not only high efficiency but also reasonable fissure to increase the taste quality of cooked GBR. Our study indicated that the fissure degree affected cooking properties of the GBR with respect to the optimum cooking time, water uptake ratio, volume expansion ratio and total solids loss. An appropriate microwave intensity of 3–4 W/g may be suitable for the microwave drying of GBR considering the drying efficiency and quality. The multi-mixed fissured kernel with fissure in range of 3–4 may be the optimal fissure range suitable for the microwave drying of GBR. Appropriated fissure amount in kernels caused by microwave drying is propitious to the improvement of cooking quality of GBR.

In a conclusion, the fissure degree in GBR kernels may be used as the control strategies for microwave drying of GBR in a manner and the evaluation means for quality attributes of cooked GBR. This study may provide a new viewpoint from the perspective of fissure to evaluate the drying quality of cereal materials such as GBR.

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