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Rice degree of milling effects on hydration, texture, sensory and energy characteristics. Part 2. Cooking using fixed, water-to-rice ratios

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ABSTRACT

The purpose was to assess the effects of degree of milling on hydration and textural characteristics of rice cooked using a range of water-to-rice ratios, and to compare the energy requirements when using these fixed water-to-rice ratios to the energy required when cooking with excess-water. Surface lipid contents (SLCs) ranged from 0.15% to 0.55% for non-parboiled rice and from 0.40% to 0.95% for parboiled rice. Cooking degree was assessed by measuring cooked-rice peak force, moisture content and percentage gelatinized kernels. Milling degree had little to no effect on cooking characteristics of all milled samples. Differences in cooking characteristics between milled and brown rice were less pronounced for parboiled than non-parboiled rice. Non-parboiled milled rice required the least energy to be 'well-cooked', followed by parboiled milled rice, non-parboiled brown rice, and parboiled brown rice (there were no significant differences between non-parboiled and parboiled brown rice). In general, excess-water cooking required more energy than fixed water-to-rice ratio cooking.

1. Introduction

As explained in Part 1[1], to assess the effect of reduced milling on the overall energy used for rice post-harvest milling and cooking, two aspects should be considered. First, because milling rice to lesser degrees requires shorter milling durations (Cooper and Siebenmorgen, 2007; Lanning and Siebenmorgen, 2011), less energy is required to mill rice when leaving more bran on kernels, which is in agreement with Roy et al. (2008). Surface lipid content (SLC), which is often used as an indicator of degree of milling (DOM), decreases as milling progresses and bran is removed from kernels. Second, rice milled to lesser degrees (greater SLCs) may require more energy to cook. The amount of energy that is required to cook rice is determined by the cooking duration, which could be affected by kernel properties, such as kernel dimensions, the amount/type of starch or protein (Juliano, 1971), and the DOM, but could also be largely determined by the rice cooking method.

Saleh and Meullenet (2007), who cooked rice with a fixed, 2:1 water-to-rice ratio in a rice cooker, reported that cooked rice moisture content (MC) increased from 67.9% to 70.5% when SLC decreased from 0.6% to 0.2% for a long-grain cultivar "Francis" that was harvested at 21.8% MC. However, there was no significant effect of SLC on cooked-rice MC for long-grain "Wells" that had 21.4% MC at harvest, suggesting that the effects of SLC on water uptake may be cultivar specific. The authors explained that the lower water uptake at greater SLCs could be due to an increase in the protein content. It is thus possible that rice with greater SLCs may have a lower water uptake rate, longer cooking duration, and greater energy required for cooking in fixed, water-to-rice ratios.

Roy et al. (2008) assessed the effect of DOM on cooking energy when using a fixed water-to-rice ratio for short- and long-grain, non-parboiled rice. The authors found that the cumulative energy use for rice dehulling, milling, and cooking was greater for brown rice than for milled rice for the cultivars studied, even though no milling was performed to obtain brown rice. However, they also reported that energy use of partially-milled rice was less than that of well-milled rice. Desikachar et al. (1965) reported that milling to a level of removing 75% of the bran was sufficient to produce rice with acceptable cooking qualities. Therefore, the overall energy required to mill and cook rice, when milling to lesser degrees, could depend on the relative magnitude of the energy used for milling compared to that used for cooking.

The effect of milling duration on DOM, and the resulting effect on milling yields has been addressed, particularly for non-parboiled rice (Cooper and Siebenmorgen, 2007; Lanning and Siebenmorgen, 2011; Mohapatra and Bal, 2006, 2007; Roy et al., 2008, 2004). Roy et al. (2004) determined the cooking duration, cooking energy and cooked-rice texture of non-parboiled and parboiled rice when using a rice cooker and water-to-rice ratios ranging from 1.5 to 2.5 and found that parboiled rice required a longer cooking duration and greater energy use than non-parboiled

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[1] Part 1 of this two-part series addressed the impacts of reduced milling of rice on the manuscript title characteristics when cooking rice in excess-water.

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rice. The effect of parboiling on cooking duration and texture of cooked rice has also been studied by Kato et al. (1983). However, there were no studies found that assessed the effect of DOM on cooking energy of parboiled rice. In addition, while some limited work has been done on the effects of DOM on cooking duration and energy requirements for cooking non-parboiled rice, more quantification is needed, particularly given that cooking duration is reported to be cultivar specific (Mohapatra and Bal, 2006).

The objectives of this manuscript, the second of a two-part series, were to: (1) determine the inter-related effects of DOM, as quantified by SLC, and water-to-rice mass ratios on cooking duration, cooked-rice texture, and energy requirements when cooking in a rice cooker; (2) compare the energy required to cook rice using fixed, water-to-rice mass ratios to that when cooking in excess-water, as quantified in Part 1.

2. Materials and methods

2.1. Rice samples

The rice lots used were the same as those described in Part 1. Fig. 1 shows the experimental design for this study, in which rice was cooked under controlled water-to-rice mass ratios. The series of tests depicted in Fig. 1 are described in the following sections.

2.2. Cooking procedure and cooking energy measurement

The amount of water relative to rice in a rice cooker is a primary factor determining cooking duration; greater water-to-rice ratios lead to longer cooking durations, since the termination of a cooking run is automatically determined by the point at which no liquid water remains in the cooker. Given that the water-to-rice ratio required to reach an acceptable texture depends on the rice chemical composition (Juliano, 1971; Juliano and Perez, 1983), rice could be undercooked, well-cooked, or overcooked depending on the water-to-rice ratio and type of rice used. Thus, to compare the energy required to cook rice having different milling degrees, it was necessary to determine the water-to-rice ratio that produced 'well-cooked' rice at each rice SLC level.

Head rice was cooked in a rice cooker (RC 101 type 2, Rival, Milford, MA) using water-to-rice mass ratios of 1.50, 1.75, 2.00, 2.25 and 2.50 for non-parboiled rice and of 2.00, 2.25, 2.50, 2.75 and 3.00 for parboiled rice. To achieve a desired water-to-rice ratio, 300 g of head rice was added to the corresponding mass of distilled water at ~20 °C in the rice cooker. Immediately after adding the rice, a cooking run was started by turning the rice cooker on; the run was completed when the rice cooker automatically turned off, which occurred when all water was absorbed by the rice or evaporated through the rice cooker vent. The cooking duration was taken as the time span between the cooker being turned on and automatically turning off. Energy measurements, as a product of instantaneous power and duration, were recorded continuously by the power meter (PROes, Electronic Educational Devices, Inc., Denver, CO) during the cooking duration; the energy required to cook the rice was taken as the cumulative energy recorded by the meter throughout the cooking run.

The cooking tests depicted in Fig. 1 were replicated and the energy required for cooking rice was measured for each replication; energy requirements were expressed on a per unit mass of uncooked rice.

2.3. Degree of cooking assessment

A primary objective was to assess the effects of DOM on textural characteristics when cooking with various water-to-rice ratios when using rice milled to a range of DOMs. Thus, several methods were used to determine rice cooking degree at the end of each cooking run. Texture analyses, cooked-rice MC, and percentage gelatinized kernels were performed in triplicate for each cooking replication following the procedures given in Part 1. Because each

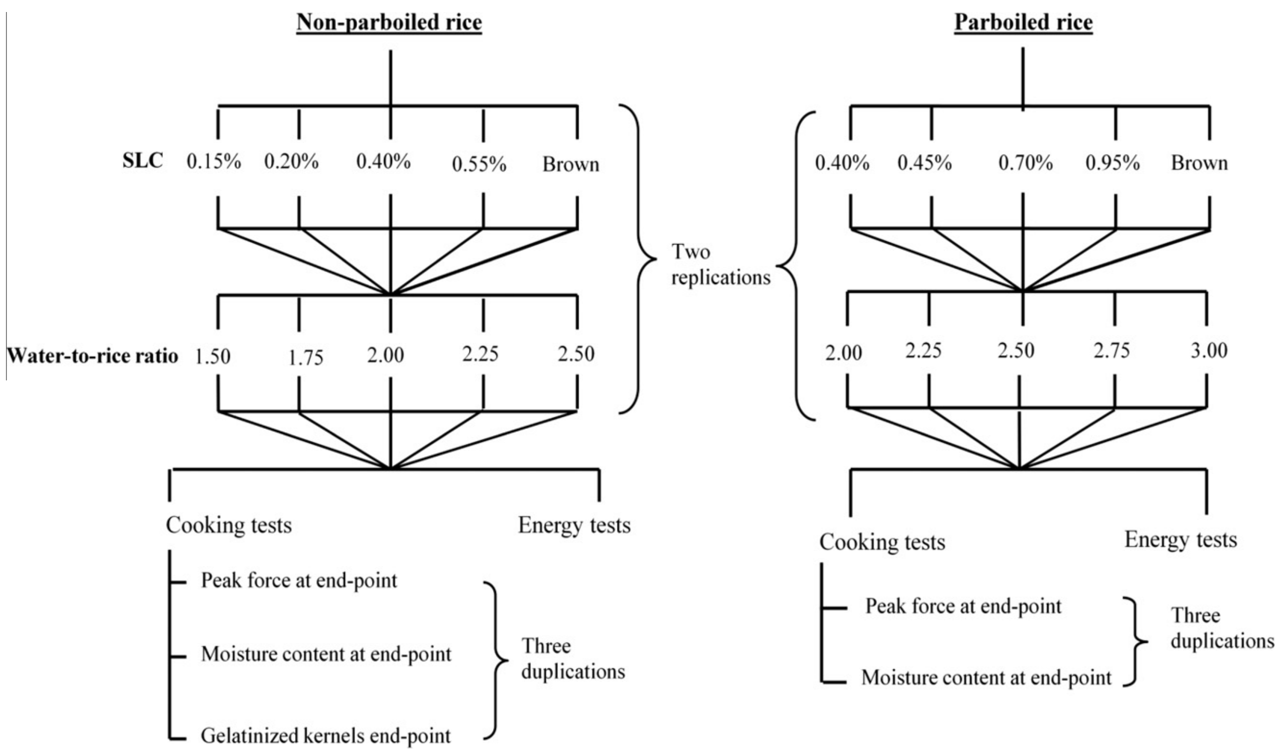

Fig. 1. Experimental design for tests in which rice was cooked under controlled water-to-rice mass ratios.

cooking run was replicated, these tests were performed six times for a given SLC/water-to-rice ratio combination.

Because parboiled rice has already been partially-gelatinized, the gelatinized-kernel method of Desikachar and Subrahmanyan (1961) is not an appropriate indicator of cooking degree of parboiled rice, and was thus not applied to parboiled rice samples. Therefore, peak force and MC of cooked rice were used as indicators of cooking degree of parboiled rice.

All statistical analyses were performed using JMP 9 Pro software (SAS Institute, Inc., Cary, NC). Significance was set at $\alpha = 0.05$ level.

3. Results and discussion

3.1. Effect of SLC on cooking duration and texture

3.1.1. Non-parboiled rice

Fig. 2 shows the effect of non-parboiled rice SLC on the duration cooked in the rice cooker, and the final rice MC, for water-to-rice ratios of 1.75, 2.00 and 2.50. There was no significant effect of SLC on cooking duration for non-parboiled rice samples having SLCs ranging from 0.15% to 0.55%, for any of the water-to-rice ratios tested. The rice cooker automatically turns off when the thermostat, which is located at the bottom of the main body of the rice cooker, detects that the temperature rises above 100 °C, indicating that all the water has been either absorbed by the rice or evaporated through the vent. Thus, for the same water-to-rice ratio, it was reasoned that samples that had similar cooking durations would have similar water absorption rates. Mohapatra and Bal (2006) explained that at high DOMs (low SLCs) the differences in cooking duration were small because most cellulosic material has been removed from rice kernels. Cooking duration of brown rice was significantly longer than that of milled rice for any given water-to-rice ratio (Fig. 2), suggesting that the water absorption rate of brown rice was slower.

Fig. 2 also shows that brown rice MC at the end of a cooking run was always less than the milled rice MC at a given water-to-rice ratio. Since brown rice had longer cooking durations than those of milled rice (Fig. 2), the amount of steam lost while cooking brown rice may be greater. Therefore, the lesser MC observed for brown rice for any given water-to-rice ratio, may be due in part to a greater amount of steam lost through the rice cooker vent while cooking, but could also be due in part to brown rice having lesser equilibrium moisture content than milled rice (Ondier et al., 2012). Park et al. (2001) reported that the MC of cooked rice decreased from 63% to 61% and the amount of water evaporated increased from 95.5 to 136.9 g when DOM decreased from 14.0% to

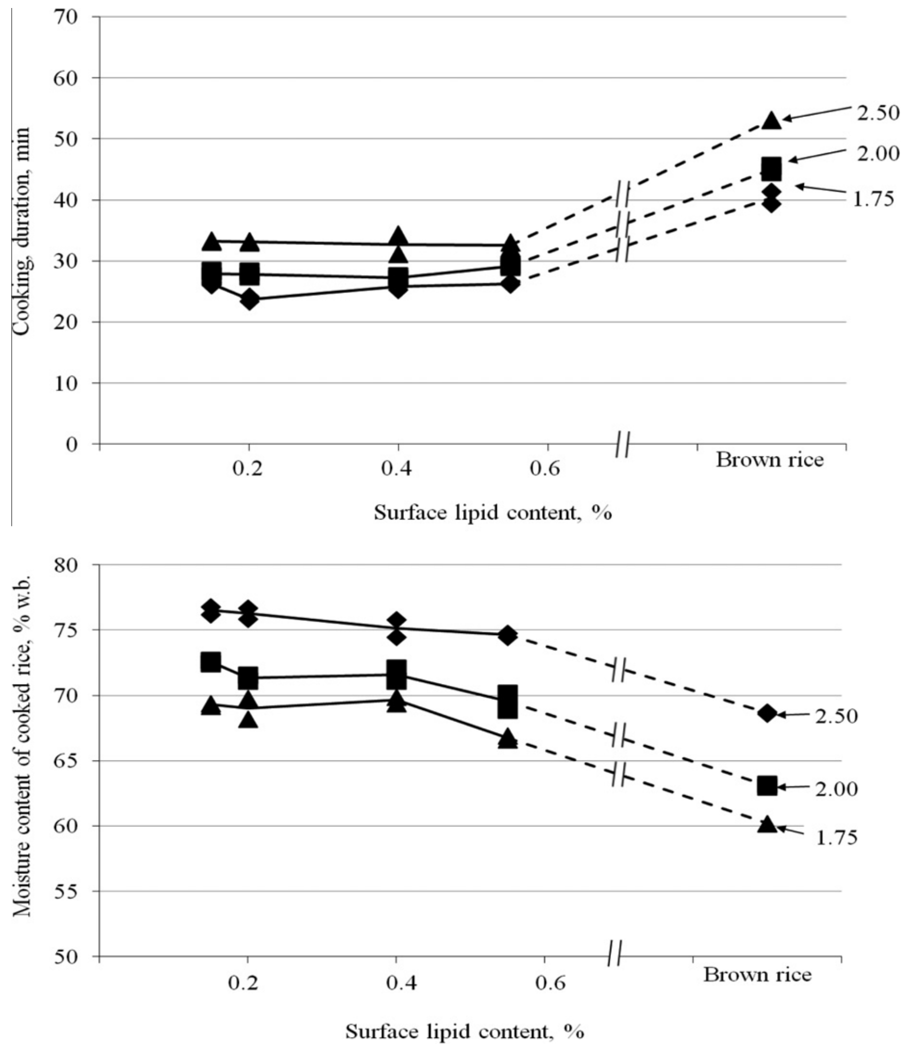

Fig. 2. Cooking duration and moisture content of non-parboiled rice with the indicated SLCs that was cooked in a rice cooker using 1.75, 2.00 and 2.50 water-to-rice ratios. Data points indicate either cooking duration measured at the end of each cooking replication or the mean of three duplications of moisture content at the end of each cooking replication.

8.0%, where DOM was expressed as [1-(weight of milled rice/weight of brown rice)] × 100. This trend is also somewhat apparent in the MC data of Fig. 2 at the 0.55% SLC level.

Fig. 3 shows the effect of SLC on hardness (peak force) and number of gelatinized kernels at 1.75, 2.00 and 2.50 water-to-rice ratios. In general, for a given water-to-rice ratio, there was no significant effect of SLC on cooked rice hardness and number of gelatinized kernels for rice samples having SLCs ranging from 0.15% to 0.55%. However, when rice was cooked using a 2.00 water-to-rice ratio, peak force of non-parboiled rice having 0.15% SLC was significantly less than that of non-parboiled rice having 0.55% SLC, and while not statistically significant, there was also such a trend for the 2.50 water-to-rice ratio. This is in agreement with Saleh and Meullenet (2007), who cooked long-grain rice using a 2.00 water-to-rice ratio and found that firmness of cooked rice with 0.2% SLC was significantly less than that of rice with 0.6% SLC. Park et al. (2001), who cooked rice using a fixed water-to-rice ratio, reported an increase in instrumental hardness from 1.25 to 2.64 g when DOM decreased (SLC increased) from 14.0% to 8.0%.

Because peak force is affected by MC (Roy et al., 2008), the greater peak force at 0.55% SLC (Fig. 3) possibly was due to a lesser MC (Fig. 2); the MC of cooked rice having 0.55% SLC was significantly less than that of rice having 0.15% SLC for the 1.75 and 2.00 water-to-rice ratios. For instance, the difference in MC of samples having 0.15% and 0.55% SLC for a water-to-rice ratio of 2.00 was 2.9 percentage points (Fig. 2), suggesting that the samples with 0.55% SLC had a slower water absorption rate than those at 0.15%. However, this speculation is not supported by cooking duration data because the cooking durations of samples having 0.55% SLC were not significantly longer than those of samples having 0.15% SLC for any water-to-rice ratio. It is possible that at 0.55% SLC, the water absorption rate was slightly slower and the amount of water vapor lost was slightly greater, leading to a minor decrease in MC of cooked rice without increasing cooking duration, and that the 0.55% SLC corresponds to the milling degree at which the amount of bran existing on the rice kernels begins to hinder water absorption inside the kernels.

It is recognized that cooking rice in a rice cooker does not ensure a completely uniform cooking treatment throughout the bulk of rice in the cooker and therefore a potential source of variability is introduced to MC and peak force measurements due to sample variability. Das et al. (2006) reported that MC of cooked rice could vary from approx. 71.0% to 75.5% from top to bottom at the center of a rice cooker and from approx. 74.0% to 75.5% from center-to-periphery at the middle layers of the rice cooker. In this study, samples for analysis were consistently taken from the geometric center of the rice cooker to minimize sampling variability.

Fig. 3 shows that brown rice had significantly greater peak force than milled rice. Similar trends were reported by Roy et al. (2008) who cooked rice using a rice cooker. Because MC of cooked brown rice was significantly less than that of milled rice, a lesser number of gelatinized kernels were expected for brown rice. However,

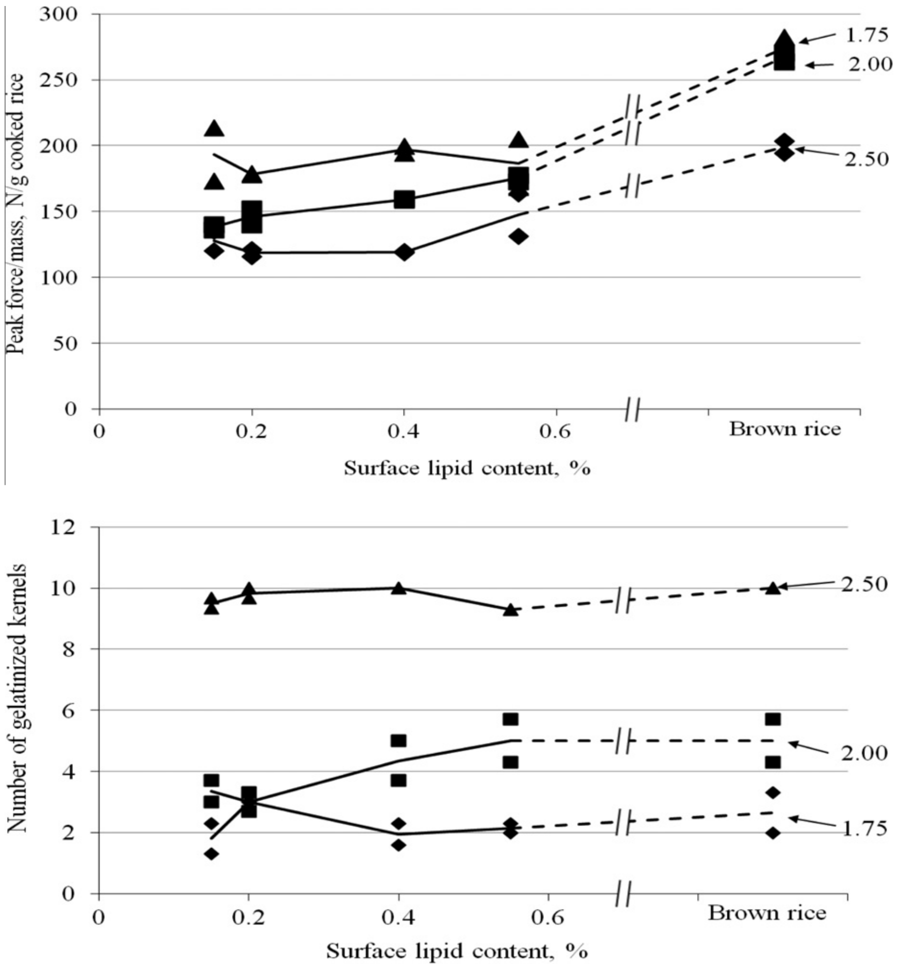

Fig. 3. Peak force and number of gelatinized kernels of non-parboiled rice with the indicated surface lipid contents that was cooked in a rice cooker using 1.75, 2.00 and 2.50 water-to-rice ratios. Data points are means of three duplications of either peak force or number of gelatinized kernels at the end of each cooking replication.

there were no significant differences in the number of gelatinized kernels between brown and milled rice samples (Fig. 3). A possible explanation could be that because cooking duration of brown rice was longer (Fig. 2), water had sufficient time to diffuse inside brown rice kernels and gelatinize starch, yet the bran layer existing on brown rice kernels still caused an increase in peak force.

3.1.2. Parboiled rice

Cooking duration and MC trends for parboiled rice were similar to those of non-parboiled rice. It is noted that the differences in cooking duration and MC between milled and brown rice were more pronounced for non-parboiled rice (Fig. 2) than for parboiled rice (Fig. 4). For instance, for a water-to-rice ratio of 2.00, the cooking duration for non-parboiled brown rice was 18 min longer than that of non-parboiled milled rice with 0.40% SLC (Fig. 2); whereas the cooking duration for parboiled brown rice was only 12 min longer than that of parboiled milled rice with 0.40% SLC (Fig. 4). This could be explained in part by Kato et al. (1983) who indicated that components such as proteins, lipids and starch may interact during parboiling. If interactions between starch and bran components (lipids and proteins) had already occurred during parboiling, then the difference in cooking duration between milled and brown rice could be less pronounced for parboiled rice than for non-parboiled rice. In addition, Subba Rao and Bhattacharya (1966) reported a greater amount of bran pigments in milled parboiled rice than in milled non-parboiled rice (both having equal milling degrees) and hypothesized that during parboiling the inner bran layers are infused into the endosperm. If this is the case, parboiled milled rice would have greater amounts of hydrophobic proteins and lipids from the bran that could lead to reduced water absorption rates and longer cooking durations, similar to those of parboiled brown rice. As such, differences in cooking kinetics between milled and brown rice would be less pronounced for parboiled rice.

Cooking durations of parboiled milled rice were greater than those of non-parboiled milled rice (Figs. 2 and 4). E.g., for a water-to-rice ratio of 2.00 and 0.40% SLC, the cooking duration of parboiled rice was 7 min longer than that of non-parboiled rice. This confirms the results of Part 1, as well as those of Sowbhagya and Ali (1991) and Roy et al. (2004), in which cooking durations of parboiled rice were longer than those of non-parboiled rice. However, this behavior was not observed for brown rice in this study (Figs. 2 and 4). E.g., for a 2.00 water-to-rice ratio, the required cooking duration of non-parboiled brown rice (45 min) was similar to that of parboiled brown rice (46 min). It is postulated that parboiling alters the structure of the bran layers of brown rice including the hydrophobic waxy cuticle of the outer surface of brown rice (Champagne et al., 2004), which offers a physical barrier to water absorption, allowing greater water absorption rates at the kernel surface of parboiled brown rice and, thus, minimizing the overall differences in water uptake during cooking between non-parboiled and parboiled brown rice.

Peak force trends for parboiled rice were similar to those of non-parboiled rice (Fig. 5). However, the differences in peak force

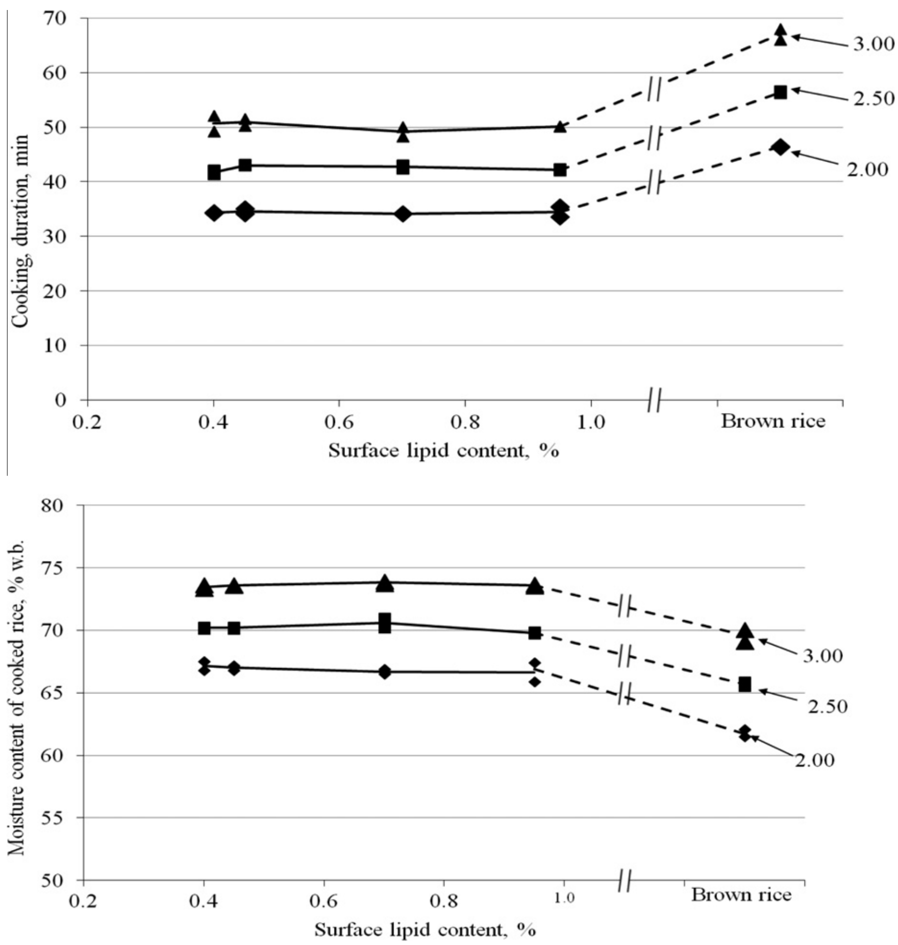

Fig. 4. Cooking duration and moisture content of parboiled rice with the indicated surface lipid contents that was cooked in a rice cooker using 2.00, 2.50 and 3.00 water-to-rice ratios. Data points indicate either cooking duration measured at the end of each cooking replication or the mean of three duplications of moisture content at the end of each cooking replication.

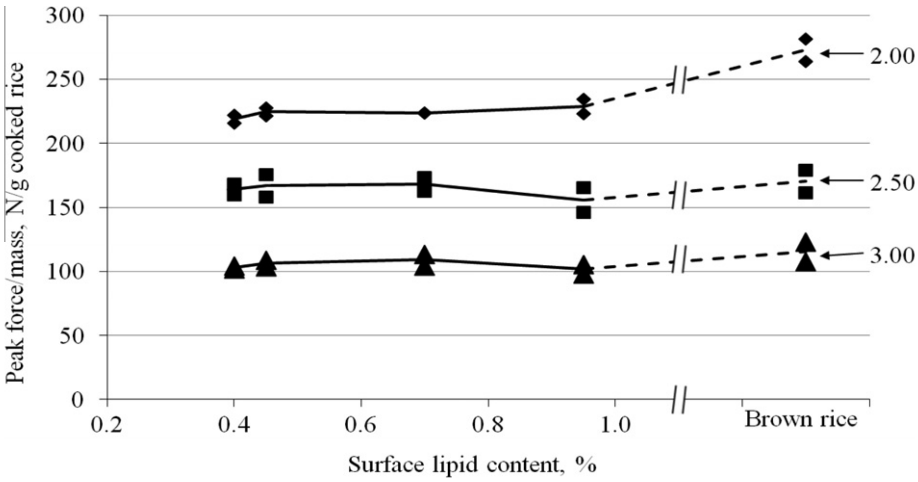

Fig. 5. Peak force of parboiled rice with the indicated surface lipid contents that was cooked in a rice cooker using 2.00, 2.50 and 3.00 water-to-rice ratios. Data points are means of three duplications of peak force measured at the end of each cooking replication.

between parboiled milled and brown rice were not significant for the 2.25, 2.50, 2.75 and 3.00 water-to-rice ratios (Fig. 5). If there were significant differences in peak force between milled and brown parboiled rice (Fig. 5), they were less pronounced than for non-parboiled rice. Peak force of parboiled milled rice was greater than that of non-parboiled milled rice (Fig. 3) at any given water-to-rice ratio/SLC combination. However, for a 2.50 water-to-rice ratio, peak force of parboiled brown rice was less than that of non-parboiled brown rice in spite of the fact that the MC of parboiled brown rice (66%) was slightly less than that of non-parboiled brown rice (68%) (Figs. 2–5).

3.2. Effect of water-to-rice ratio on cooking duration and texture

Cooking duration increased linearly with water-to-rice ratio for all SLCs for both non-parboiled and parboiled rice. This was expected because as the water-to-rice ratio increases the amount of water that has to be absorbed by the rice or vented from the rice cooker increases prior to the cooker automatically turning off. For instance, for non-parboiled rice with 0.40% SLC, cooking duration increased linearly ($r^2 = 0.97$) from 23 to 33 min when the water-to-rice ratio increased from 1.50 to 2.50 (data not shown). Similarly, cooking duration of parboiled rice with 0.40% SLC increased linearly ($r^2 = 0.98$) from 33 to 51 min when water-to-rice ratios ranged from 2.00 to 3.00.

As shown in Figs. 2 and 4, the MC of cooked rice also increased as water-to-rice ratio increased for any given SLC. The resultant impact of this increased rice MC due to increased water-to-rice ratio is illustrated in Fig. 6, which showed that peak force decreased as water-to-rice ratio increased for all SLC levels. This is in agreement with Juliano and Perez (1983) and Roy et al. (2008) who reported that hardness (peak force) of cooked rice decreases as MC increases. Fig. 6 clearly demonstrates that water-to-rice ratio impacts the texture of rice. Similar results were obtained for parboiled rice (data not shown).

3.3. Effect of water-to-rice ratio on cooking energy

There were no significant differences in the energy required to cook samples milled to the various SLCs among either the non-parboiled or parboiled rice samples for any water-to-rice ratio (data not shown); these trends were similar to those reported by Roy et al. (2008). Thus, an average cooking energy value for each experimental design, water-to-rice ratio for each rice set was calculated. Energy requirements to cook milled non-parboiled rice in a rice cooker were 490, 545, 600, 642 and 696 Wh/kg uncooked rice for 1.50, 1.75, 2.00, 2.25 and 2.50 water-to-rice ratios, respectively; to similarly cook non-parboiled brown rice were 745, 878, 962, 1057, 1113 and 1188 Wh/kg uncooked rice for 1.50, 1.75, 2.00, 2.25 and 2.50 water-to-rice ratios; to cook milled parboiled rice in a rice cooker were 723, 803, 880, 964 and 1049 Wh/kg uncooked rice for 2.00, 2.25, 2.50, 2.75 and 3.00 water-to-rice ratios, respectively. Energy requirements to cook parboiled brown rice were 985, 1090, 1205, 1341, and 1403 Wh/kg, uncooked rice for 2.00, 2.25, 2.50, 2.75 and 3.00 water-to-rice ratios. The water-to-rice ratio has a large impact on the energy required to cook rice from any of the sets.

3.4. Degree of cooking determination and selection of water-to-rice ratios

Because as water-to-rice ratio increased, cooked rice hardness decreased considerably for both non-parboiled and parboiled rice (Fig. 6) and cooking energy proportionately increased, it was necessary to determine the water-to-rice ratio that produced 'well-cooked' rice in order to compare cooking-method energy requirements. The intention was thus to select the water-to-rice ratios that ensured that rice of the various sets, cooked using fixed water-to-rice ratios, was cooked to the same degree ('well-cooked') as that cooked using excess-water. In Part 1, gelatinization, moisture content and peak force kinetics were used to determine the cooking durations required to attain 'well-cooked' rice when cooking rice from each set in excess-water in a beaker (Table 3; Part 1). Subsequently, rice from each set was cooked in a rice cooker for a duration, determined from the beaker tests, which produced 'well-cooked' rice. At the end of each rice cooker run, the cumulative energy and rice MCs were measured and reported in section 2.5 of Part 1.

Because of the importance of cooked-rice MC to cooking degree, it was reasoned that if rice cooked using fixed water-to-rice ratios was cooked to the same, rice-set specific MC as rice cooked in excess-water, each rice set would be cooked to the same degree regardless of the cooking method. Therefore, the MCs of 'well-cooked' rice when cooking with excess-water were used as target MCs for determining the appropriate ratios when cooking using the fixed water-to-rice ratio method. These target MCs were 75%, 69%, 72% and 63% for non-parboiled milled, non-parboiled brown, parboiled milled and parboiled brown rice, respectively.

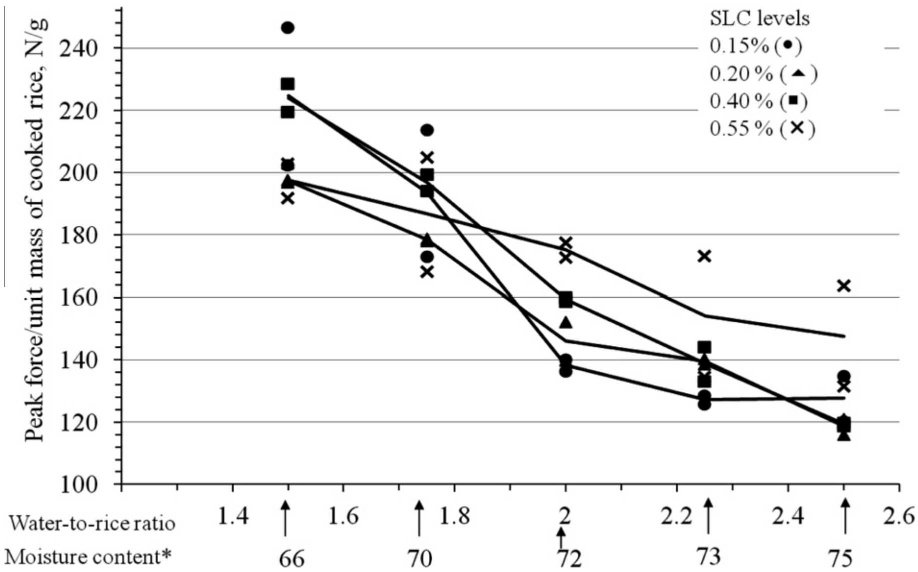

Fig. 6. Peak force per unit mass cooked rice as a function of water-to-rice ratio for non-parboiled rice that had been milled to the indicated surface lipid content (SLC) levels. Data points indicate are means of three duplications of peak force measured at the end of each cooking replication. *Mean values of three duplications of moisture content measured at the end of the cooking replication for the various water-to-rice ratios.

All non-parboiled milled samples were undercooked when using water-to-rice ratios below 2.50 based on the fact that cooked-rice MC was below the target of 75%, at any SLC (Fig. 2). The 2.50 water-to-rice ratio was selected to obtain 'well-cooked' non-parboiled milled rice, because cooked-rice MCs were 76%, 76%, 75%, 75% for 0.15%, 0.20%, 0.40% and 0.55% SLCs, respectively (Fig. 2). Similarly, a 2.50 water-to-rice ratio was selected for non-parboiled brown rice since this produced a brown rice MC of 69% (Fig. 2), which is equal to the target MC.

All parboiled milled rice samples cooked using water-to-rice ratios below 2.75 had MCs below the target of 72%, indicating that samples were undercooked compared to excess-water cooking. For the 2.75 water-to-rice ratio, MCs of cooked parboiled milled rice were equal to the target of 72%, regardless of the SLC level

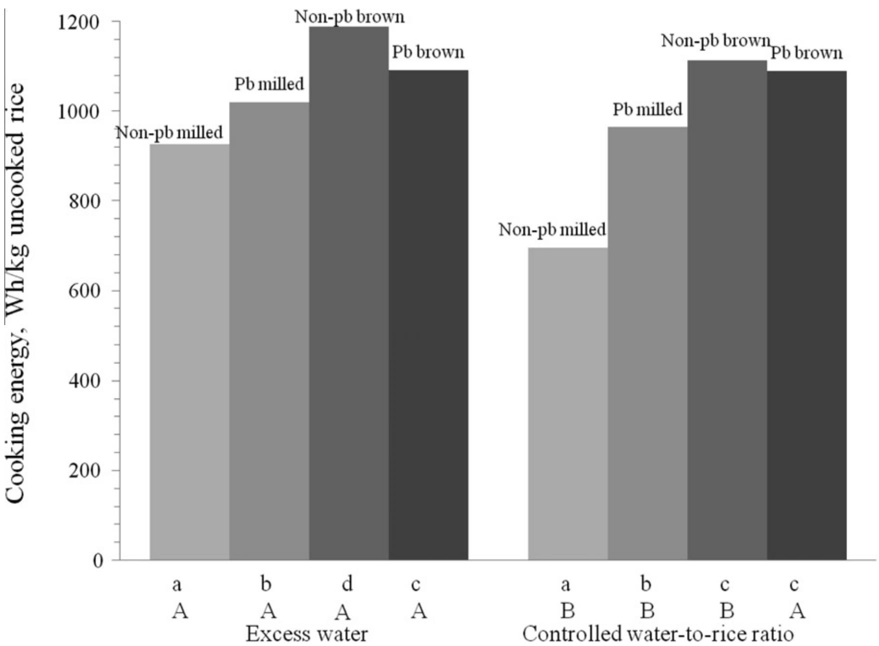

Fig. 7. Energy required to cook rice for the indicated rice sets when using excess-water and controlled water-to-rice ratio cooking methods. Rice sets were cooked to the same degree when using both methods as indicated by reaching the same target MC for each rice set. Rice samples cooked in excess-water using a water-to-rice ratio of 3.50 (data obtained from Part 1) were cooked for 22, 26, 34 and 29 for non-parboiled milled, parboiled milled, non-parboiled brown and parboiled brown rice, respectively. Rice sets cooked using fixed water-to-rice ratios were cooked using ratios of 2.50 for non-parboiled milled and brown rice, 2.75 for parboiled milled rice and 2.25 for parboiled brown rice. Mean values of cooking energy within a cooking method with different lowercase letters are significantly different ($p < 0.05$). Mean values of cooking energy obtained by the different cooking methods within a given rice set with different upper-case letters are significantly different ($p < 0.05$).

(data not shown). Parboiled brown rice achieved a MC of 64% when using a water-to-rice ratio of 2.25, similar to the target of 63% MC obtained with excess-water cooking. Thus, the 2.75 water-to-rice ratio was selected as the water-to-rice ratio to obtain 'well-cooked' parboiled milled rice and 2.25 was chosen for parboiled brown rice.

Based on these water-to-rice ratios, the corresponding energy values listed in section 3.3 were plotted in Fig. 7 as those required to attain 'well-cooked' rice using fixed water-to-rice ratios. Non-parboiled milled rice required the least energy to be 'well-cooked' (696 Wh/kg uncooked rice), followed by parboiled milled rice (964 Wh/kg uncooked rice), non-parboiled brown rice (1188 Wh/kg uncooked rice), and parboiled brown rice (1090 Wh/kg uncooked rice); there were no significant differences between non-parboiled and parboiled brown rice. Roy et al. (2008) reported that a milled Japonica rice variety (DOMs ranging from 2% to 10% bran removal) required ~270 Wh/kg cooked (contrasted to uncooked rice as expressed in the study herein) rice to attain an acceptable texture, whereas non-parboiled brown rice required 425 Wh/kg cooked rice. In addition, Roy et al. (2008) reported that energy requirements to cook an Indica variety to an acceptable soft texture in a rice cooker were 266, 300 and 419 Wh/kg cooked rice for 9.4%, 5.4% and 0% DOM, respectively. For comparison purposes, cooking energy values obtained in this study, in which Indica rice was used, were also expressed on a per unit mass of cooked rice basis; cooked rice mass was calculated by adjusting the initial, 300 g mass at the initial MC, to the cooked rice mass at the target MC of each rice set. The cooking energy values obtained for non-parboiled milled rice were 210 Wh/kg cooked rice and 410 Wh/kg cooked rice for non-parboiled brown rice; both are similar to those reported by Roy et al. (2008).

3.5. Comparison of energy use between cooking methods

Fig. 7 shows that, in general, cooking rice using fixed water-to-rice ratios required significantly less energy than that of cooking in excess-water to obtain 'well-cooked' rice. It is noted that the energy requirements for excess-water used in Fig. 7 correspond to a water-to-rice ratio of 3.5, which, as explained in Part 1, was determined to be the minimum required to ensure excess-water cooking. Cooking in excess-water required 33.0% more energy than that of fixed water-to-rice ratio cooking to obtain 'well-cooked' non-parboiled milled rice, 6.8% more energy for parboiled milled rice and 6.7% more energy for non-parboiled brown rice; there were no significant differences in cooking energy between cooking methods for parboiled brown rice. It is to be recalled that while the cooking energy values were obtained for both methods in a rice cooker, a primary procedural difference was that in the excess-water method, water was first heated to 98 °C and then rice was added, whereas in the fixed water-to-rice ratio method, water and rice were simultaneously heated and cooked from the start of the cooking process. It is possible that cooking using a fixed water-to-rice ratio was more energy efficient because rice absorbed water while the mixture was being heated; when cooking in the excess-water method, the rice began absorbing water after the water was heated to 98 °C.

It is noted that the value of the water-to-rice ratio plays an important role in determining the energy requirements to cook rice, as shown in section 3.3. As explained in Part 1, for the excess-water cooking method, visual observation determined the minimum water-to-rice ratio in which water was left in the rice cooker after the duration required to 'well-cooked' rice, thus ensuring an excess-water approach. Because the water-to-rice ratios generally used in common practice of cooking in excess-water are much greater, the energy values shown in Fig. 7 for excess-water cooking are considered to be correspondingly conservative.

4. Conclusions

The degree of milling of rice, as indicated by surface lipid content, had little to no effect on cooking duration, cooking energy and cooked-rice texture when SLC ranged from 0.15% to 0.55% for non-parboiled rice and from 0.40% to 0.95% for parboiled rice when cooking using fixed water-to-rice ratios. Brown rice required significantly greater cooking duration and had a harder texture than milled rice for both non-parboiled and parboiled rice. Because these milled rice/brown rice differences in cooking characteristics were more pronounced for non-parboiled rice than for parboiled rice, it is reasoned that the parboiling process reduced cooking response differences between milled and brown rice. Parboiled milled rice required longer cooking durations and had greater peak force than non-parboiled milled rice, for any water-to-rice ratio. However, cooking durations of parboiled brown rice were similar to those of non-parboiled brown rice while peak force of parboiled brown rice was less than that of non-parboiled brown rice for most water-to-rice ratios. It is speculated that parboiling changes not only the endosperm starch, but also the bran layers of the brown rice kernel, and that these bran layer changes would play an important role in hydration and peak force kinetics of brown rice during cooking.

For the selected water-to-rice ratios for each rice set, non-parboiled milled rice required the least energy to be 'well-cooked', followed by parboiled milled rice, parboiled brown rice, and non-parboiled brown rice (there were no significant differences between non-parboiled brown and parboiled brown rice). In addition, cooking rice using a fixed water-to-rice ratio required less energy than excess-water cooking for non-parboiled milled, parboiled milled and non-parboiled brown rice. However, there were no differences in energy requirements between cooking methods for parboiled brown rice.

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