MILLING YIELDS AND PHYSICOCHEMICAL PROPERTIES OF LONG-GRAIN RICE THICKNESS FRACTIONS

B. C. Grigg, T. J. Siebenmorgen

ABSTRACT. Thickness grading of rice (Oryza sativa L.) can divert thin, chalky kernels to a secondary processing stream, thus improving milling yields of the primary stream. However, the quantity and functionality of the secondary stream may impact processing operations. Rough rice of multiple long-grain cultivar lots was either left unfractined (Unf) or thickness graded into fractions comprising A (< 1.7 mm), B (1.7 << 1.9 mm), C (< 1.9 << 2.0 mm), D (2.0 << 2.05 mm), and E (> 2.05 mm). Mass distribution of rough rice; milled rice yield (MRY), and head rice yield (HRY); kernel dimensions of brown rice; crude protein content (CP) and chalkiness of brown and head rice; and paste viscosities of head rice flour were determined for each cultivar lot/fraction. For all cultivar lots, MRY, HRY, and kernel dimensions increased with increasing thickness fraction, while chalkiness and CP decreased. Milling yields were the greatest for the C/D/E fractions. Including the C fraction (C/D/E) with the primary stream resulted in an average 17.4 percentage point mass increase compared to D/E alone; this with minimal impacts to milling yields of the primary stream. Weighted-average MRYs and HRYs of the combined C/D/E fractions increased by up to 6.9 and 12.8 percentage points, respectively, compared to Unf rice. The A/B fractions were generally of greater chalkiness and CP; however, paste viscosities remained relatively consistent with those of the C/D/E fractions. Thickness grading could be justified on the merits of improved milling yields, kernel uniformity, and reduced chalkiness of the primary processing stream. A small change in the thickness grading procedure decreased the quantity of the secondary stream; moreover when milled, the secondary stream retained functionality similar to the primary stream.

Keywords. Chalkiness, Crude protein, Functionality, Head rice yield, Kernel dimensions, Milled rice yield, Thickness grading.

The United States, ranked 5th worldwide in rice exported in 2014 (USDA-ERS, 2014), accounts for a relatively small portion of world rice production. Appearance affects the marketability of milled rice (McClung, 2013). In particular, chalkiness and kernel dimensions impact rice quality (Lisle et al., 2000; Bergman et al., 2004; USDA-FGIS, 2009). Chalkiness may also affect sensory properties and end-use functionality of rice (Kim et al., 2000; Lisle et al., 2000; Ashida et al., 2009; Chun et al., 2009).

Chalkiness is linked to the process of starch accumulation in the rice endosperm (Kim et al., 2000; Lisle et al., 2000; Patindol and Wang, 2003; Ashida et al., 2009; Patindol et al., 2014). Chalkiness of rice is affected by climate during reproductive growth (Counce et al., 2005; Ambardekar et al., 2011; Lanning et al., 2011). Increased chalkiness can also be associated with less than optimal harvest scheduling. Premature harvest can result in immature, chalky kernels (Kocher et al., 1991). Harvest delays, whether for logistical reasons or extended in-field drying, can result in a greater proportion of late-developing/chalky, but mature kernels within the harvested rice (Kester et al., 1963; Mohapatra et al., 1993; Lu et al., 1995; Chen et al., 2008; Espinosa-Mendoza et al., 2012). These late-developing/chalky kernels arising from secondary panicle positions were of reduced starch concentration (Mohapatra et al., 1993) and amylose content (Cheng et al., 2007).

While impacting rice quality, chalkiness also reduces milling yields (Counce et al., 2005; Lanning et al., 2011), which largely determine the economic value of rough rice. Milled rice yield (MRY) represents the mass fraction of dried, rough rice that remains as milled rice, which includes both head rice and broken kernels. Head rice yield (HRY) represents the mass fraction of rough rice that remains as head rice, synonymous with “whole kernels” (USDA-FGIS, 2009) and defined as well-milled rice kernels three-fourths or more of the original kernel length. Well-milled rice refers to the degree of milling (DOM), the extent of bran removal from brown rice during the milling operation. The bran and germ account for the majority of lipids in the rice kernel (Godber and Juliano, 2004); thus, DOM can be quantified in terms of surface lipid content (SLC) of milled rice (Hogan and Deobald, 1961; Miller et al., 1979; Pomeranz et al., 1975). Increasing DOM (reducing SLC) invariably increases the mass removed from rice kernels, thus decreasing MRY (Wadsworth, 1994) and HRY (Sun and Siebenmorgen, 1993; Lanning and Siebenmorgen, 2011). Achieving maximum HRY is important, as head rice is more valuable than...
broken kernels. Thus, a goal of the milling operation is to mill rice only to a desired SLC; avoiding over-milling and maximizing MRY and HRY.

Kernel uniformity can impact milling operations. At lesser DOM, long-grain rice milled in bulk, and subsequently fractioned as milled rice, resulted in greater SLC of the thinnest kernel fraction (<1.49 mm) as compared to the other kernel fractions (Chen et al., 1998). Under-milling of thin kernels within bulk rice can impact rice functionality (Perdon et al., 2001; Saleh et al., 2008), as well as sensory issues such as rancidity associated with storage of under-milled kernels (Wadsworth, 1994). Given the impacts of elevated SLC values on storage of milled rice, millers tend to over-mill the thick kernels in a bulk lot in order to simultaneously mill the thin kernels to the desired DOM; thus, increasing milling duration and cost, and sacrificing milling yield in the process.

Thickness grading has been proposed as a means of improving kernel uniformity by diverting thin kernels of rough rice to alternate processing streams (Matthews et al., 1982; Chen et al., 1998). Matthews and Spadaro (1976) also indicated that breakage of milled rice was greatest in the thinnest fraction, two- to six-times that of other fractions, regardless of cultivar. Jindal and Siebenmorgen (1994) showed that thicker kernels of rice produced dramatically greater HRY when compared to thinner kernels. Sun and Siebenmorgen (1993) reported greater HRY for the thickest kernels when compared to bulk, unfractioned rice of three long-grain cultivars. In the case of the cultivar Newbonnet, the weighted average HRY from separately-milled thick and thin fractions exceeded that of bulk rice (Sun and Siebenmorgen, 1993). Rohrer et al. (2004) reported that when fractioned as rough rice prior to milling, thin kernels milled to a lower SLC and HRY compared to thicker kernels at the same milling duration. Thus, if milled as a separate processing stream, thin kernels would require shorter milling durations, likely resulting in decreased breakage and increased milling yield. More recently, Grigg and Siebenmorgen (2013; 2015) have shown that thickness grading of rough rice can be used to divert thin, chalky kernels to a secondary processing stream, while retaining thicker kernels in a primary processing stream of rice with reduced chalkiness and improved milling yields.

Potential advantages of thickness grading of rough rice include greater milling yields, reduced chalkiness, and improved kernel-uniformity of milled rice of the primary processing stream. However, potential drawbacks of thickness grading include the additional processing operations, as well as the quantity and functionality of thin kernels associated with the secondary processing stream. For three of four cultivar lots, Grigg and Siebenmorgen (2013) reported mass fractions of 15% or less of thin kernels diverted to a secondary processing stream when fractioning with a 2.0-mm width screen; however, the fourth cultivar lot had a considerably greater thin-kernel fraction, comprising 33% of mass. In subsequent research, Grigg and Siebenmorgen (2015) thickness graded multiple lots of two cultivars harvested in 2012, reporting thin-kernel (< 2.0 mm) mass fractions ranging from 20% to 43%. The objectives of this research were two-fold: first, to determine whether the mass fraction of the primary stream of kernels could be increased, while retaining improved milling yields and reducing chalkiness; and second, to quantify physicochemical and functional properties associated with the various thickness fractions that may further justify the process of thickness grading of long-grain rice.

**Materials and Methods**

**Sample Procurement and Preparation**

Both MRY and HRY can be affected by multiple factors, including variety/genetics, production and harvest practices, and environmental conditions. Thus, five cultivar lots of long-grain rice were selected (table 1), comprising both pureline and hybrid cultivars. All selected cultivars ranked among the top cultivars produced in Arkansas in 2014 (Hardke, 2015). All cultivar lots were produced using recommended management practices (Hardke, 2013) and combine-harvested at multiple locations in either 2012 or 2013 as indicated in table 1.

Using a dockage tester (Model XT4, Carter-Day, Minneapolis, Minn.), rough rice of all cultivar lots was cleaned to remove dockage and unfilled kernels. The cleaned cultivar lots were then conditioned to 12.0±0.5% moisture content (MC, wet basis) using a climate-controlled chamber (26°C and 56% relative humidity), regulated by a stand-alone conditioner (5580A, Parameter Generation & Control, Black Mountain, N.C.). Post-conditioning MC of rough rice was measured using a moisture meter (AM5200, Perten Instruments, Hägersten, Sweden). Conditioned lots were stored at 4±1°C prior to use. Bulk samples were equilibrated to room temperature (22±1°C) for at least 24 h prior to thickness grading and sample preparation.

**Thickness Grading of Rough Rice**

For each lot, 1 kg of rough rice was maintained as unfractioned (Unf) rice, while 20 to 24 kg of rough rice was graded according to thickness using a precision sizer (ABF2, Carter-Day, Minneapolis, Minn.). The precision sizer was sequentially equipped with rotary screens (30-cm diameter) with 30-mm long slots of either 1.7-, 1.9-, 2.0- or 2.05-mm width. Lots were screened in 2-kg batches, and each batch was sequentially screened beginning with the 1.7-mm screen and ending with the 2.05-mm screen. For each screening, the precision sizer was operated at 90 rpm for 4 min as described

<table>
<thead>
<tr>
<th>Cultivar Lot</th>
<th>Source</th>
<th>Year</th>
<th>MRY (%)</th>
<th>HRY (%)</th>
<th>SLC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL151 (pureline)</td>
<td>Strip trial, Harrisburg, Ark.</td>
<td>2012</td>
<td>70.5</td>
<td>60.5</td>
<td>0.4</td>
</tr>
<tr>
<td>CL XL745 (hybrid)</td>
<td>Strip trial, Osceola, Ark.</td>
<td>2013</td>
<td>71.9</td>
<td>59.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Roy J (pureline)</td>
<td>Strip trial, Osceola, Ark.</td>
<td>2013</td>
<td>67.3</td>
<td>54.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Wells (pureline)</td>
<td>Strip trial, Bell City, Mo.</td>
<td>2012</td>
<td>71.4</td>
<td>59.1</td>
<td>0.3</td>
</tr>
<tr>
<td>XL753 (hybrid)</td>
<td>Farm field, Pocahontas, Ark.</td>
<td>2013</td>
<td>71.9</td>
<td>62.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

HRY’s were adjusted to a degree of milling of 0.4% surface lipid content according to Pereira et al. (2008).

---

916 APPLIED ENGINEERING IN AGRICULTURE
by Grigg and Siebenmorgen (2015). In addition to Unf rice, the resulting thickness fractions comprised A (< 1.7 mm), B (1.7 ≤ 1.9 mm), C (1.9 < 2.0 mm), D (2.0 ≤ 2.05 mm), and E (> 2.05 mm). Following thickness grading, milling yields and physicochemical properties of the samples were determined. Mass distribution across thickness fractions was determined on a single 2-kg batch of each lot, and was expressed as a percentage of the original 2-kg sub-lot mass.

**MILLING PROPERTIES**

Four replicate, 150-g samples of rough rice of each cultivar lot/fraction (including Unf) were prepared and maintained at 22±1°C for up to one week prior to milling. Samples were dehulled using a laboratory sheller (THU 35B, Satake Corporation, Hiroshima, Japan) with a roller clearance of 0.048 cm according to Siebenmorgen et al. (2006b). The resultant brown rice samples were milled (McGill No. 2, RAPSCO, Brookshire, Texas; equipped with a 1.5-kg mass on the lever arm, situated 15 cm from the milling chamber centerline) for a 30-s duration. Both MRY and HRY were determined, with head rice being separated from broken kernels using a sizing device (611, Grain Machinery Manuf. Corp., Miami, Fla.) and maintained for determination of physical properties. Head rice SLC, the mass percentage of extracted lipid relative to the original head rice, was determined by scanning approximately 50 g of head rice kernels using near-infrared-reflectance (NIR, DA7200, Perten Instruments, Hägersten, Sweden) (Saleh et al., 2008). Head rice yield (HRY) was adjusted to a SLC of 0.4% according to the method of Pereira et al. (2008).

**PHYSICOCHEMICAL PROPERTIES**

Brown rice properties were determined by first dehulling a 100-g subsample of rough rice using a laboratory sheller (THU 35B, Satake Corp., Hiroshima, Japan) with a clearance of 0.048 cm between the rollers. Any remaining rough rice or broken kernels were then removed prior to subsequent analyses. Dimensions, comprising length, width, and thickness of 400 brown rice kernels were quantified using a rice image analyzer (1A, Satake Corp., Hiroshima, Japan).

Crude protein content (CP) of either brown rice or head rice was determined as the average of two scans of a 50-g subsample of intact kernels using near-infrared reflectance (NIR, DA7200, Perten Instruments, Hägersten, Sweden). Prior to NIR detection of CP for this study, NIR results from a sample set comprising brown rice and head rice samples of various cultivars and DOM were calibrated with corresponding results using approved method 46-16.01 (AACC International, n.d.). Crude protein was reported as a mass percentage of protein (wt basis).

Chalkiness of either brown rice or head rice was determined using a digital scanning system (WinSeedle Pro 2005a™, Regent Instruments Inc., Sainte-Foy, Quebec, Canada) in the manner of Ambardekar et al. (2011). Chalkiness was reported as a percentage of total scanned area of 200 intact kernels of either brown rice or head rice.

Paste viscosities of head rice flour were determined according to approved method 61-02.01 (AACC International, n.d.), where 15 g of head rice from each sample was ground in a cyclone mill (3010-30, UDY, Fort Collins, Colo.) fitted with a 100-mesh (0.5-mm) sieve to produce flour. Moisture content of each flour sample was determined by drying duplicate 2-g subsamples at 130°C for 2 h in the previously mentioned convection oven. Viscosities were determined on a paste of one 3-g subsample of rice flour in 25 mL of distilled water (with minor adjustments to account for MC of the rice flour) with a viscometer (RVA Super 4, Newport Scientific Pty, Ltd, Warwwood, NSW, Australia). The flour paste was held at 50°C for 1.0 min, heated to 95°C at 12°C min⁻¹, held at 95°C for 2.5 min, and cooled to 50°C at 12°C min⁻¹. Peak viscosity (PV), trough viscosity (TV), and final viscosity (FV) were quantified, and PV, FV and the differential viscosity of breakdown (BD = PV – TV) were reported as dynamic viscosity (cP).

**DATA ANALYSIS**

Statistical software (JMP Pro 11, SAS Institute, Cary, N.C.) was used to analyze the data. Analysis of variance (ANOVA, α=0.05) was conducted and means separated using the Tukey-Kramer Honestly Significant Difference procedure (HSD, P=0.05). Statistical significance (P<0.05) was determined, and significant differences were indicated using separate-letter reporting.

**RESULTS AND DISCUSSION**

**MILLING YIELDS AND MASS DISTRIBUTION OF THICKNESS GRADED RICE**

For all cultivar lots, thickness grading of rough rice resulted in fractions of differing MRYs (fig. 1a). The MRYs of the A fraction were the least, and MRYs of the A and B fractions were significantly less than those of the C, D, and E fractions (> 1.9-mm thickness of rough rice). The MRYs of the D and E fractions (> 2.0-mm thickness of rough rice) were statistically equivalent. For the pureline cultivars, comprising CL151, Roy J, and Wells, MRYs of the C fraction were also statistically equivalent to those of the D and E fractions. The MRYs of the C fraction of the hybrid cultivar lots of CL XL745 and XL753 were slightly less than those of the D and E fractions; however, MRYs of the C fraction were still considerably greater than those of the A and B fractions. For all cultivars, MRYs of the C, D, and E fractions were all statistically equal to, or greater than, those of Unf rice.

The HRYs of the A and B fractions were consistently the lowest when compared to the C, D, and E fractions and Unf rice, regardless of cultivar (fig. 1b). Data for the A and B fractions agree with previous reports of greater breakage and reduced HRYs in association with the thinnest rice kernels (Matthews and Spadaro, 1976; Jindal and Siebenmorgen, 1994). For all cultivar lots, HRYs of the E fraction were the greatest. For the pureline cultivar lots CL151 and Wells, HRYs of the C, D, and E fractions were statistically equivalent. For Roy J, the remaining pureline cultivar lot, HRYs of the D and E fractions were equivalent, and were greater than the HRY of the C fraction. For the CL XL745 and XL753 hybrid cultivar lots, HRYs significantly increased with increasing thickness from the C to the D and E fractions. For the CL151, CL XL745, and XL753 cultivar lots, HRYs of the A fraction exceeded that of the B fraction. A quantity of dehulled...
brown-rice (apparently the result of shattering during combine harvesting) was observed to have passed through to the A fraction during thickness grading, thus altering HRYs and physicochemical properties of the A fraction yet to be discussed. However, this potential admixture of thicker kernels into the A fraction (thinnest kernels) would likely occur with most combine harvesting operations.

The HRYs of the C, D, and E fractions of the pureline cultivar lots (CL151, Roy J, and Wells) exceed HRYs of Unf rice (fig. 1b). For the hybrid cultivar lots comprising CL XL745 and XL753, HRYs of only the D and E fractions exceeded that of Unf rice. However, the D and E fractions of the hybrid cultivar lots comprised a greater percentage of kernel mass as compared to pureline cultivar lots (fig. 2).

Mass distributions across the A through E fractions varied according to cultivar lot (fig. 2). A concern arising from preceding research (Grigg and Siebenmorgen, 2015) was the quantity of rice being diverted into the secondary stream in order to isolate thin, chalky kernels. When considering the primary stream of kernels, only the D and E fractions (D/E) would have been retained using the previous 2.0-mm thickness cut-off. The mass percentage of the retained D/E stream ranged from 43% to 79%, with the D/E stream of the CL XL745 and XL753 hybrid lots comprising 71% and 79% of mass, respectively, and the CL151, Roy J, and Wells pureline lots comprising only 57%, 47%, 43% of mass, respectively. Were the thickness cut-off shifted to a 1.9-mm thickness, the C fraction would also be retained with the primary stream (C/D/E). Mass percentages of the C/D/E primary stream ranged from 66% (Wells) to 87% (XL753); an increase of 8 to 23 percentage points (pp) depending on cultivar lot, with 20 pp or larger increases associated with the pureline cultivar lots. Alone, the substantial increase in the mass percentage of the C/D/E primary processing stream would likely justify inclusion of the C fraction.

When considering the weighted average of all fractions (ABCDE), compared to Unf rice, MRYs modestly increased between 0.1 and 0.9 pp, and HRYs increased between 0.5 and 2.0 pp, depending on the cultivar lot (fig. 3). These data for weighted-average HRYs agree with the report of Sun and Siebenmorgen (1993). However, when considering only the fractions retained in either the D/E or C/D/E primary streams, MRYs increased considerably compared to Unf rice. Using such weighted averages, milling only the D/E fractions increased MRYs from 2.6 to 7.3 pp, and HRYs from 3.1 to 15.4 pp. However, changing the primary stream to C/D/E still considerably increased milling yields when compared to Unf rice; with increased MRYs from 2.3 to 6.9 pp, and HRYs from 3.1 to 12.8 pp, depending on the cultivar lot. Expanding the primary stream to include the C fraction (C/D/E) minimally reduced weighted-average milling yields compared to the original D/E, while increasing the mass percentage of the C/D/E primary stream by an average of 17.4 pp. Thus, considering the trade-off between milling yields and mass distribution, including the C fraction in the primary stream appears to be a strong option. However, physicochemical properties of fractions, particularly the thin fractions, should be considered in addition to milling yields.

**Physicochemical Properties of Thickness Graded Rice**

Quantities of rough rice were insufficient for developing the relationship between milling duration and DOM for all cultivar lots/fractions; thus, milling all cultivar lots/fractions to a specific DOM (i.e., 0.4% SLC) was not achievable. A
30-s milling duration was selected, and resulted in SLCs of 0.4% or less for all cultivar lots/fractions, although with considerable variation across cultivar lots (tables 1 and 2). There were no consistent trends of SLCs in response to thickness grading (data not included). As indicated in table 2, the difference between minimum and maximum DOM was 0.1 pp or less across thickness fractions, respective of cultivar lot. Within a cultivar lot, this range was not considered to be practically significant, as this laboratory routinely reports a range of 0.1 pp when milling to a specified SLC (e.g., 0.4±0.05%). However, differences in mean SLCs among cultivar lots reached levels of up to 0.17 pp. While HRYs were corrected for DOM, measured physicochemical properties were not; the impacts of DOM on these properties have not been established mathematically. Thus, direct comparison of physicochemical properties of head rice among thickness fractions of a cultivar lot, and overall trends among cultivar lots, were considered valid; while direct comparisons of fractions among cultivar lots were not made. For consistency, further discussion of both brown rice and head rice physicochemical properties will focus on differences among thickness fractions within a cultivar lot.

Thickness grading of rough rice effectively separated brown rice kernels into fractions of distinct length, width, and thickness (fig. 4a-c). Regardless of cultivar lot, all brown rice dimensions increased with increasing thickness fraction, with the exception of the A fraction (fig. 4a-c). Mean dimensions of the A fraction exceeded those of the B fraction, and sometime the C fraction, depending on dimension and cultivar lot. Trends for kernel dimensions of the A fraction support the previously discussed supposition of admixed large kernels of brown rice. Presence of the larger kernels within the A fraction account for unexpected HRY results, as well as physicochemical properties to be discussed. As a result of this admixture of thick kernels within the A fraction, much...
of the discussion henceforth will focus on the comparison of the B through E fractions. With the exception of the A fraction, these kernel dimension data agree with reports of Matthews et al. (1982) and Chen et al. (1998); thus demonstrating that improved kernel uniformity can be achieved by diverting kernels of smaller dimensions to a secondary processing stream.

With the negative impact of brown rice chalkiness on HRY (Lanning et al., 2011; Grigg and Siebenmorgen, 2015), one key objective of this research was to isolate the chalkiest kernels. Except for the XL753 lot, brown rice chalkiness significantly differed across thickness fractions for all cultivar lots, with the general trend being decreased chalkiness with increasing kernel thickness (fig. 5a). Brown rice chalkiness was statistically the greatest in the B fraction of the pureline lots comprising CL151, Roy J, and Wells. Although not statistically greatest, brown rice chalkiness in the B fraction of the XL753 lot was numerically greater than the remaining fractions. Brown rice chalkiness of the thickest E fraction was either the least, or among the lowest when compared to the remaining fractions of a cultivar lot. Maximal levels of chalkiness were expected in the thinnest fractions, as previously observed (Grigg and Siebenmorgen, 2013; 2015); however, average brown rice chalkiness of the A fractions was less than observed with the B fractions, again resulting from the admixture of thick kernels of lesser chalkiness.

While brown rice chalkiness has been shown to reduce HRYs, chalkiness of head rice affects grading (USDA-FGIS, 2009) and functionality (Kim et al., 2000; Lisle et al., 2000; Ashida et al., 2009; Chun et al., 2009). Head rice chalkiness (fig. 5b) followed similar trends to that of brown rice, with head rice chalkiness of the B fraction being the greatest for all cultivar lots. Head rice chalkiness of the E fraction was the least when compared to other fractions within any cultivar lot. For all cultivar lots maximal chalkiness of head rice was observed with the B fraction. From these results, it appears that changing the thickness cut-off, such that the primary processing stream was composed of the C/D/E thickness fractions, would still divert the chalkiest kernels to the secondary processing stream. This secondary stream of more-chalky, uniformly-thin kernels (A and B fractions) could be shunted to parboiling, as suggested by Luh and Mickus (1991), or to production of flour with potentially improved characteristics arising from chalkiness (Ashida et al., 2009).

Brown rice CP decreased with increasing thickness fraction for all cultivar lots (fig. 6a), with exception of the A fraction as previously discussed. Considering the progression from the B fraction to the E fraction, brown rice CP decreased by a range of 0.5 to 1.7 pp, dependent on cultivar lot, agreeing with previously reported trends (Grigg and Siebenmorgen, 2013). Greater brown rice CP levels in the thin kernels (A/B secondary processing stream) could improve utility as a food or feed ingredient. The secondary stream having greater CP and chalkiness could result in a high-protein brown rice flour, with potentially beneficial flour properties resulting from increased chalkiness (Ashida et al., 2009).

Trends of head rice CP were similar to those of brown rice, although differences between fractions were of lesser magnitude (fig. 6b). Again considering the transition from thin (B) to thick (E) kernels, head rice CP generally decreased between 0.4 and 0.6 pp for all cultivar lots. Thus, head rice CP was relatively stable across thickness fractions.

Figure 5. Chalkiness of (A) brown rice and (B) head rice of the resulting thickness fractions of the indicated long-grain rice cultivar lots. Rough rice was thickness graded into fractions comprising A (< 1.7 mm), B (1.7 << 1.9 mm), C (1.9 << 2.0 mm), D (2.0 << 2.05 mm), and E (> 2.05 mm). Comparisons are valid within a cultivar, and columns with a different letter are significantly different (P<0.05).

Figure 6. Crude protein (CP) content of (A) brown rice and (B) head rice of thickness fractions of the indicated long-grain rice cultivar lots. Rough rice was thickness graded into fractions comprising A (< 1.7 mm), B (1.7 << 1.9 mm), C (1.9 << 2.0 mm), D (2.0 << 2.05 mm), and E (> 2.05 mm). Comparisons are valid within a cultivar, and columns with a different letter are significantly different (P<0.05).
of any cultivar lot, suggesting that the greater differences observed with brown rice CP across thickness fractions resulted from CP within the bran layer and germ, which are removed during milling.

Paste viscosities of head rice (flour) are reported for all cultivar lots and fractions (fig. 7a-c). Head rice PV tended to increase with increasing thickness fraction except for the A fraction (fig. 7a); again with trends for the A fraction likely resulting from admixed thicker kernels. For all cultivar lots except the CL XL745 lot, PVs of the E fraction were significantly greater than those of the B fraction. When comparing the B and E fractions, overall increases in PV ranged from approximately 50 to 280 cP, dependent on the cultivar lot. As head rice chalkiness (fig. 5b) and CP (fig. 6b) decreased, PVs increased (fig. 7a), in agreement with previous reports (Martin and Fitzgerald, 2002; Ashida et al., 2009; Chun et al., 2009). Kester et al. (1963) did not discuss the impacts of chalkiness, but attributed reduced PVs to increased amylase activity. Siebenmorgen et al. (2006a) also reported reduced PVs in association with thin kernels of fractioned long-grain rice; with reduced PVs occurring in conjunction with increased α-amylase activity and decreased amylose content. Cheng et al. (2007) reported increased amylose content in early-developing kernels of primary panicle positions, which comprise the kernels of the thicker kernel fractions. Amylose content was not determined here; however, these PV data, along with previous reports (Siebenmorgen et al., 2006a; Cheng et al., 2007), suggest the likelihood of decreased amylose contents with decreasing thickness fraction.

Bergman et al. (2004) identified BD as an indicator of stability under heat and shear stress; thus, increased BD would indicate lesser stability of the head rice (flour) paste. For all of the cultivar lots, the thinner kernels (A/B fractions) tended to have lesser BDs in comparison to the thicker kernels (C/D/E fractions) (fig. 7b), although slightly elevated BD observed with the A fractions, again supporting the supposition of admixture of thicker kernels. While significant differences between thickness fractions were observed, increased BDs with increasing kernel thickness from the B to the E fraction ranged from approximately 30 (CL XL745) to 210 cP (Wells). Pureline cultivar lots (CL151, Roy J, and Wells) tended to have the greatest BD differentials across thickness fractions, while the hybrid cultivar lots (CL XL745 and XL753) tended to more stable. The minimal trend of reduced BD in association with thinner kernels would suggest that these kernel fractions may be more suited to processing operations requiring cooked rice or flour.

Bergman et al. (2004) also indicated that FV, representative of the ability to re-form a paste after cooking and cooling, is the most commonly used parameter defining the processing quality of a rice sample. While the overall magnitude of FVs varied according to cultivar lots, FVs were relatively consistent across thickness fractions of any cultivar lot (fig. 7c), such that differences between minimum and maximum FVs were minimal, ranging from 10 (CL XL745) to 155 cP (XL753). Thus, the impact of thickness fraction on FVs was likely of practical insignificance.

**CONCLUSIONS**

Thickness grading of rough rice resulted in a trend of increasing MRY and HRY with increasing kernel thickness. Improved weighted-average MRYs and HRYs were observed for the primary processing stream, comprising either the D/E (kernels > 2.0-mm thickness) or the C/D/E (kernels > 1.9-mm thickness) fractions. By adjusting the primary stream to include the C/D/E fractions, the mass of the primary processing stream was increased considerably without appreciable effects on milling yields. Kernels containing the greatest chalkiness concentrations were successfully diverted to a secondary processing stream, even when the primary processing stream comprised the C/D/E fractions. The resulting secondary processing stream comprised the immature chalky kernels, or late-developing chalky kernels of secondary panicle positions.

Kernel length, width, and thickness of brown rice increased with increasing thickness fraction. Thus, diverting the thinnest kernels to secondary processing would result in a primary stream of kernels of increased and more-uniform...
dimensions. Brown rice CP decreased with increasing kernel thickness. While a similar trend was observed for head rice CP, differences across thickness fractions were minimal within a cultivar lot. Together with decreased chalkiness, decreased CP contributed to a general trend for increasing viscosities as kernel thickness increased; however, viscosity differences across thickness fractions were minor, and likely of little practical significance.

Thickness grading to remove the thin kernels of secondary quality would create a primary processing stream characterized by improved milling yields, greater kernel length and uniformity, and reduced chalkiness. Thickness grading would also create an extra process operation/flow of the thinner, chalkier kernels. However, the secondary stream of rough rice could be diverted to parboiling operations or production of a high-protein, whole-grain flour. Head rice of the secondary stream was found to have similar CP and paste viscosities to that of the primary processing stream. Thus, milled rice flour produced from the secondary stream of thinner kernels would likely be of similar functionality. The economic and logistic implications on commercial milling operations have not been fully considered. However, these data indicate that thickness grading could be justified on the merits of improved milling yields and kernel uniformity, and reduced chalkiness of the primary processing stream.

ACKNOWLEDGEMENTS
The authors express their thanks to the staff of the University of Arkansas Rice Processing Program for sample processing and analysis. The authors acknowledge the Arkansas Rice Research and Promotion Board and the corporate sponsors of the University of Arkansas Rice Processing Program for financial support of this project.

REFERENCES


