

IMPACTS OF KERNEL THICKNESS AND ASSOCIATED PHYSICAL PROPERTIES ON MILLING YIELDS OF LONG-GRAIN RICE

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ABSTRACT. Rice milling yields are impacted by kernel physical properties, which may vary by kernel thickness. Four rice lots, comprising Wells and XL753 long-grain cultivars of both superior and inferior milling yields, were thickness graded into three fractions: thin (<2.00 mm), medium (2.00 << 2.05 mm), and thick (>2.05 mm). Milled rice yield (MRY), head rice yield (HRY), rough-rice bulk density (ρ_b), and both brown-rice chalky area (chalkiness) and fissured-kernel percentage (FKP), were determined for each lot and fraction. The MRYS of thick kernels exceeded those of thin kernels for all lots, and those of medium kernels for inferior lots. The HRYs of thick kernels were less than those of medium kernels, significantly so for inferior lots. For all lots, medium kernels had greater HRYs than thin kernels. Thick kernels had greater HRYs than thin kernels for three of the four lots evaluated. Overall, ρ_b increased, and chalkiness decreased, with increasing kernel thickness. The FKP varied by cultivar, increasing with increased thickness for only the Wells lots. Using uni-variate linear modeling, ρ_b effectively predicted MRY ($R^2=0.91$, $P<0.0001$), but predicted HRY to a lesser degree ($R^2=0.14$, $P<0.01$). Chalkiness poorly predicted MRY ($R^2=0.25$, $P<0.001$) and HRY ($R^2=0.24$, $P<0.001$), and FKP marginally predicted HRY ($R^2=0.46$, $P<0.0001$). Multi-variate linear modeling, comprising ρ_b , chalkiness, and FKP, improved the prediction of MRY ($R^2=0.93$, $P<0.0001$), and greatly improved the prediction of HRY ($R^2=0.83$, $P<0.0001$). Measurement of these physical properties could help anticipate the need for thickness grading, which could concentrate and partition chalky or fissured kernels from the bulk stream, thus improving milling yields.

Keywords. Bulk density, Chalkiness, Head rice yield, Kernel fissuring, Milled rice yield, Milling quality, Thickness grading.

The economic value of rough rice (*Oryza sativa* L.) is largely determined by milled rice yield (MRY, the mass fraction of unprocessed, rough rice that remains as milled rice, including both head rice and broken kernels) and head rice yield [HRY, the mass fraction of rough rice that remains as head rice, synonymous with “whole kernels” and defined as well-milled rice kernels three-fourths or more of the original kernel length (USDA-FGIS, 2009)]. Well-milled rice refers to the degree of milling (DOM), the extent of bran removal from brown rice during the milling operation. Increased DOM is invariably accompanied by increased loss of mass, indicated by decreased MRY (Wadsworth, 1994), and by decreased HRY (Sun and Siebenmorgen, 1993; Lanning and Siebenmorgen, 2011). Thus, the goal of rice processing is to avoid over-milling of rice, carefully controlling DOM

(Wadsworth, 1994), and thereby maximizing MRY and HRY.

Monitoring lot-to-lot variability (Lanning and Siebenmorgen, 2011; Siebenmorgen et al., 2006c) and adjusting milling parameters is one strategy for reducing variability in DOM between lots. Size-grading techniques, such as thickness grading, could reduce milling variability inherent within rice lots, as described by Chen et al. (1998). Size grading has been shown to be beneficial to milling operations for other cereal grains, with improved dehulling efficiency and grain uniformity of oat (*Avena sativa*) (Doehlert et al., 2002, 2004), and improved milling yield and flour properties of grain sorghum (*Sorghum bicolor*) (Lee et al., 2002). Thickness grading of rice has been proposed as a means of improving kernel uniformity by removing the thin kernels to alternate processing streams, such as flour or parboiled rice (Matthews et al., 1982; Luh and Mickus, 1991).

Matthews and Spadaro (1976) indicated that breakage of rice during milling was greatest in the thinnest fraction, two to three times that of other fractions, regardless of cultivar; thus, removal of thin kernels would improve HRY of the remaining rice. Evaluating long-grain cultivars, Grigg and Siebenmorgen (2013) reported a trend for improved MRY, and significantly improved HRY, when thin kernels were removed prior to milling. Greater HRY of thicker kernels resulting from removal of the thinnest

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rice kernels has also been shown by Sun and Siebenmorgen (1993).

Rohrer et al. (2004) reported that, when fractionated as rough rice prior to milling, thin kernels yielded a lower SLC and HRY compared to thicker kernels when milled for the same duration. Thus, thinner kernels would require a shorter milling duration, possibly resulting in decreased breakage and increased milling yield if milled as a separate processing stream. Defects such as chalkiness may also be associated with thin, incompletely-filled rice kernels. Chalky kernels often break during milling, thus reducing HRY (Webb, 1985). Compared to thicker kernels, the endosperms of thinner kernels contain less starch (Matthews et al., 1981; Siebenmorgen et al., 2006a) with a reduced amylose-to-amylopectin ratio (Matthews et al., 1981). Chalkiness, increased by elevated nighttime air temperatures during grain filling (Ambardekar et al., 2011; Lanning et al., 2011), has been 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). Chalkiness is an important factor for U.S. rice exports, and the domestic market downgrades chalky rice (USDA-FGIS, 2009).

Head rice yield is also reduced by kernel fissuring, the result of rapid moisture adsorption by kernels of low moisture content in the field (Siebenmorgen and Jindal, 1986; Lan and Kunze, 1996), or of conditions occurring during the drying process (Schluter and Siebenmorgen, 2007). Siebenmorgen et al. (1997) suggested that thicker, bolder kernels were more susceptible to fissuring than thinner kernels, a concept supported by Jindal and Siebenmorgen (1994). While thickness grading has been shown to partition thin, chalky kernels (Grigg and Siebenmorgen, 2013), the use of thickness grading to partition thicker, fissured kernels has not been reported. Thus, bulk lots of both superior and inferior milling quality (HRY of the bulk, unfractionated rice) were selected to determine whether thickness grading could concentrate and partition both chalky and fissured kernels to secondary processing streams, thus improving milling yields of the remaining, primary processing stream.

MATERIALS AND METHODS

SAMPLE PROCUREMENT AND PREPARATION

Four lots (table 1), comprising Wells (pureline) and XL753 (hybrid) long-grain rice cultivars of both superior (+) and inferior (-) milling quality (HRY), were selected. All lots were produced using recommended management practices and harvested in September of 2012. Using a dockage tester (Model XT4, Carter-Day, Minneapolis, Minn.), lots were cleaned to remove dockage and unfilled kernels. The cleaned lots were then conditioned to 12.0±0.5% (wet basis) moisture content using a climate-controlled chamber (26°C and 56% relative humidity), regulated by a stand-alone conditioner (Model 5580A, Parameter Generation & Control, Black Mountain, N.C.). Harvest moisture content (HMC) of rough rice was field determined and reported by the producer. Post-conditioning

Table 1. Source, harvest moisture content (HMC), milled rice yield (MRY), head rice yield (HRY), and bulk density (ρ_b) of unfractionated rough rice.

Lot ^[a]	Source	HMC (%) ^[b]	MRY (%)	HRY (%)	ρ_b (kg m ⁻³)
Wells+	Strip trial, Bell City, Mo.	14	73 a ^[c]	61 a	577
Wells-	Strip trial, Forest City, Ark.	17	72 a	34 b	566
	Research plots ^[d] , Stuttgart, Ark.	18	71 a	55 a	562
XL753+	Research plots ^[e] , Keiser, Ark.	18	71 a	40 b	561
XL753-	Ark.				

^[a] Lots comprised Wells and XL753 long-grain rice cultivars of both superior (+) and inferior (-) milling quality lots harvested during the 2012 season. All rice was milled to a surface lipid content of 0.4±0.05%.

^[b] Field determined HMC, wet basis.

^[c] Comparisons within a milling yield category (MRY or HRY) are valid between lots of a cultivar. Means followed by the same letter are not significantly different ($P>0.05$).

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moisture content of rough rice was measured by drying duplicate samples at 130°C for 24 h in a convection oven (Model 1370FM, Sheldon Mfg. Inc., Cornelius, Ore.) (Jindal and Siebenmorgen, 1987). 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, 20 to 24 kg of rough rice was graded according to thickness using a precision sizer (Model ABF2, Carter-Day, Minneapolis, Minn.) equipped with rotary screens (30 cm diameter) with 30-mm long slots of either 2.00- or 2.05-mm width. For each screening, the precision sizer was operated at 90 rpm for 4 min. Using a precision sizer was a departure from the use of a dockage tester, previously described by Grigg and Siebenmorgen (2013). However, advantages of the precision sizer were two-fold: first, availability of a wider variety of screens in 0.05-mm increments; and second, improved sorting efficiency resulting from easily controlled residence time during grading. Introducing the 2.05-mm grading to that of the 2.00-mm grading reported by Grigg and Siebenmorgen (2013) enabled partitioning of the thickest kernels. The resulting thickness fractions comprised thin (< 2.00 mm), medium (2.00 mm << 2.05 mm), and thick (> 2.05 mm). Following thickness grading, milling and physical properties of the samples were determined.

MILLING PROPERTIES

A preliminary analysis was conducted for each lot and fraction (including unfractionated) of rice to determine the milling duration required to attain the desired DOM. Duplicate 150-g samples of both unfractionated and fractionated rough rice of each lot were dehulled using a laboratory sheller (THU 35B, Satake Corporation, Hiroshima, Japan); a clearance of 0.048 cm between the rollers was selected as to remove the greatest proportion of

hulls without impacting MRY or HRY as reported by Siebenmorgen et al. (2006b). The resultant brown-rice samples were milled (McGill No. 2, RAPSCO, Brookshire, Texas; equipped with a 1.5-kg weight on the lever arm, situated 15 cm from the milling chamber centerline) for durations of 10, 20, 30, and 40 s in order to develop relationships between DOM and milling duration; thus, allowing determination of the milling duration required to achieve the desired DOM for each lot and fraction, as indicated by $0.4 \pm 0.05\%$ surface lipid content (SLC).

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, Model DA7200, Perten Instruments, Hägersten, Sweden) (Saleh et al., 2008). The SLC of randomly selected samples were periodically verified using a lipid extraction system (Avanti 2055, Foss North America, Eden Prairie, Minn.) according to the method described by Matsler and Siebenmorgen (2005), a modification of AACC Intl. Method 30-20 (AACC Intl., 2000).

Four replicate, 150-g samples of rough rice of each lot and fraction (including unfractionated) were prepared and maintained at $22 \pm 1^\circ\text{C}$ for up to one week prior to milling. These samples were milled to the desired DOM ($0.4 \pm 0.05\%$ SLC) as previously described. The SLCs of random head rice samples were also verified using the aforementioned lipid extraction system. Both MRY and HRY were determined, with head rice being separated from broken kernels using a sizing device (Model 61, Grain Machinery Manuf. Corp., Miami, Fla.) and maintained for determination of physical properties.

PHYSICAL PROPERTIES OF ROUGH AND BROWN RICE

In addition to milling properties, physical properties of both rough rice and brown rice were determined. Bulk density of rough rice (ρ_b) was determined using a filling hopper (Seedburo Equipment Co, Des Plaines, Ill.) as described by Fan et al. (1998).

Brown-rice properties were determined by first dehulling four replicate 100-g samples of rough rice (unfractionated and fractionated) as previously described for milling operations. However, for quantification of brown-rice properties, the roller clearance was increased from 0.048 cm to 0.053 cm in order to prevent any possible sheller-induced breakage. Any remaining rough rice or broken kernels were then removed prior to analyses. Using a scanning system (WinSeedle Pro 2005a™, Regent Instruments Inc., Sainte-Foy, Quebec, Canada), brown-rice chalky area (chalkiness) as a percentage of kernel area was determined (Ambardekar et al., 2011). Fissured-kernel percentage (FKP) was visually determined for brown-rice kernels using a grain-scope (Model TX-200, Kett Electric Laboratory, Tokyo, Japan) designed specifically for observing the exterior quality of rice kernels. On evaluation of 200 brown-rice kernels, a kernel was counted as fissured if one or more fissures were detected, and FKP represents the number percentage of fissured kernels.

DATA ANALYSIS

Statistical software (JMP release 10.0, SAS Institute, Cary, N.C.) was used to analyze the data. Analysis of variance (ANOVA, $\alpha=0.05$) was conducted and means separated using the Tukey-Kramer Honestly Significant Difference procedure (HSD, $P=0.05$). In relating physical property impacts on MRY and HRY, both uni- and multi-variate linear regression were conducted. For regression analyses, model coefficients, the coefficient of determination (R^2) and statistical significance (P) were computed.

RESULTS AND DISCUSSION

PROPERTIES OF BULK RICE

Unfractionated MRYs of superior and inferior lots within each cultivar were not significantly different (table 1). However, differences in HRYs were substantial, with HRY of Wells+ being 27 percentage points greater than Wells-, and HRY of XL753+ being 15 percentage points greater than that of XL753- (table 1). Reduced HRYs for the unfractionated, inferior lots appeared to be related to chalkiness and FKP (fig. 1). When compared to superior lots, there was significantly greater chalkiness observed in the inferior lots of both Wells and XL753 (fig. 1). Likewise, the FKP was greater in inferior lots of both cultivars (fig. 1). No direct link between FKP and HMC was observed, as the only rice with HMC substantially lower than the optimal of 19% to 22% (Siebenmorgen et al., 2007) was the superior Wells+ lot (table 1). For the inferior lots, the near-optimal HMC did not preclude the possibility of drying and rapid-rewetting events prior to harvest, thus causing an increase in FKP (fig. 1). Superior and inferior lots of each cultivar were produced using recommended management practices, although the lots were sourced from different producers, at different locations and under different microclimates. However, this discussion focuses on post-harvest thickness grading and physical properties of the resultant thickness fractions, as

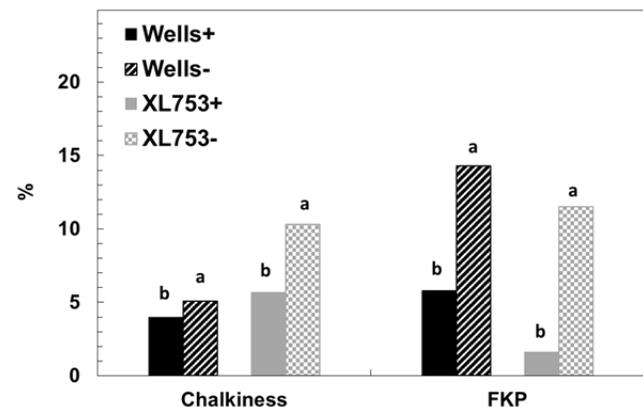


Figure 1. Brown-rice chalky area (chalkiness) and fissured-kernel percentage (FKP), for four lots of rice harvested in 2012, comprising Wells and XL753 cultivars of both superior (+) and inferior (-) milling quality. Chalkiness is expressed as a percentage of scanned kernel area, and FKP is expressed as a number percentage of fissured kernels. Bars represent the mean of four replicate samples. Comparing lots within a cultivar, values of chalkiness or FKP followed by the same letter are not significantly different ($P>0.05$).

related to milling properties, rather than being concerned with the causes of differences in measured physical properties.

THICKNESS GRADING OF ROUGH RICE

Initially, thickness grading was to proceed as a single pass over a 2.0-mm screen (Grigg and Siebenmorgen, 2013). Figure 2a illustrates the mass fractions of kernels <2.00-mm and >2.00-mm thickness resulting from this single pass strategy. Thickness grading of rough rice resulted in mass percentages for the >2.00-mm fractions ranging from 57% to 77% (fig. 2a), approximately 10 percentage points less across the range of lots than the 66% to 89% previously observed (Grigg and Siebenmorgen, 2013). Grigg and Siebenmorgen (2013) suggested a shift to greater kernel thickness and uniformity with recently released cultivars. However, with the two cultivars represented here, there was greater variability in thickness distribution between the lots of a given cultivar, than between cultivars (fig. 2a). These data suggest that the production environment, including soil-, water-, and fertility-management, along with the climate during kernel development, had as much or more impact on the distribution of kernel thickness than did cultivar.

For all lots, the >2.0-mm kernels comprised the majority of the mass. However, for both cultivars there was a noticeable trend for a greater mass of thicker kernels in the lots with inferior milling quality (fig. 2a). As chalkiness has

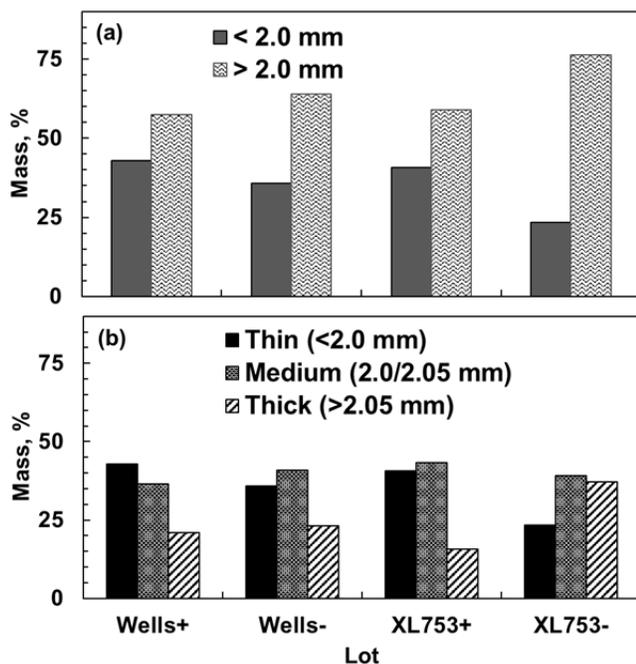


Figure 2. Mass percentages resulting from thickness grading rough rice of four lots harvested in 2012, comprising Wells and XL753 cultivars of both superior (+) and inferior (-) milling quality. Mass percentages are based on the thickness grading of a 2-kg representative sample of each lot. Figure (a) represents size grading with a 2.00-mm screen only, resulting in <2.00 mm and >2.00 mm thickness fractions as previously reported by Grigg and Siebenmorgen (2013), while fig. (b) represents further subdivision, resulting in thin (<2.00 mm), medium (2.00<<2.05 mm), and thick (>2.05 mm) thickness fractions.

been shown to be more prevalent in thinner kernels (Grigg and Siebenmorgen, 2013), this suggests that decreased HRYs for the unfractionated, inferior lots (table 1) may be associated with increased fissuring of the thicker, bolder kernels, as previously reported (Jindal and Siebenmorgen, 1994; Siebenmorgen et al., 1997). As the >2.00-mm fraction comprised kernels that would constitute the primary processing stream under this thickness-grading protocol (Grigg and Siebenmorgen, 2013), a further thickness grading of the >2.00-mm fraction was added to determine if the greater portion of fissured kernels was concentrated in the very thickest kernels, thus enabling this thickness fraction to be partitioned and transferred to an alternate processing stream, such as parboiling.

Thus, the >2.00-mm fraction was thickness-graded with a 2.05-mm screen, resulting in the previously-described thin-, medium-, and thick-kernel fractions, potentially creating a medium-kernel stream with reduced fissured kernels, reduced chalkiness, and improved milling characteristics. This thickness-grading procedure will be the basis of further discussion. The mass percentage of the thin kernels ranged from 25% to 42% (fig. 2b). The superior lots, both Wells+ and XL753+, had the greatest mass percentages of thin kernels, approximately 42% for each (fig. 2b). The mass percentage of medium kernels generally exceeded that of thin kernels, and was greater than that of thick-kernels for all lots evaluated (fig. 2b). A trend existed for greater mass percentage of thick kernels in inferior lots, 2 and 21 percentage points for Wells and XL753 cultivars, respectively (fig. 2b).

MILLING YIELD AND PHYSICAL PROPERTIES OF THICKNESS FRACTIONS

Agreeing with the trend reported by Grigg and Siebenmorgen (2013), MRY increased with increased kernel thickness for all lots (fig. 3a). For superior lots of both cultivars, there were no differences in MRY between medium and thick kernels; however, for the inferior lots the MRY of thick kernels was greater than that of medium kernels (fig. 3a). The MRYs of thin kernels were less than those of unfractionated rice for all lots evaluated (fig. 3a). For the superior lots, Wells+ and XL753+, MRYs of both medium and thick kernels exceeded those of unfractionated rice (fig. 3a). Thus, the removal of the thin kernels increased MRY for both superior and inferior rice lots. For inferior lots, the thick kernels had greater MRYs, and medium kernels equivalent MRYs, when compared to unfractionated rice (fig. 3a).

The HRYs of thin kernels were significantly less than those of medium kernels, and excepting the inferior Wells lot, were also significantly less than those of thick kernels in all lots (fig. 3b). The general trend for decreased HRYs of thin kernels occurred even though the DOM was equivalent to that of medium and thick kernels, and the trend was consistent with previous reports (Mathews and Spadaro, 1976; Rohrer et al., 2004; Grigg and Siebenmorgen, 2013). Counter to the trends observed with MRYs (fig. 3a), the HRYs of thick kernels were significantly less than those of medium kernels, with the exception of Wells+ where there was still a trend for a 1.5 percentage point

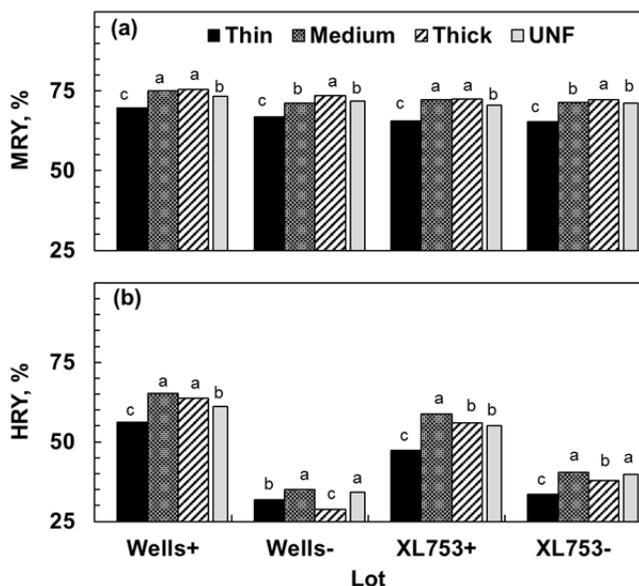


Figure 3. Milled rice yield [MRY] (a) and head rice yield [HRY] (b) of thickness fractions and unfractioned (UNF) rice of four lots harvested in 2012, comprising Wells and XL753 cultivars of both superior (+) and inferior (-) milling quality. Thickness grading of rough rice resulted in thin (< 2.00 mm), medium (2.00<<2.05 mm), and thick (>2.05 mm) fractions. All samples were milled to 0.4±0.05% surface lipid content. Bars represent the mean of four replicate samples. Within yield category and lot, values followed by the same letter are not significantly different ($P>0.05$).

decrease in HRY of thick kernels (fig. 3b). This trend of reduced HRYs of thick kernels in comparison to medium kernels, agrees with the report of Sun and Siebenmorgen (1993) for kernels thicker than 2.05 mm.

The HRYs of thin kernels were less than those of unfractioned rice (fig. 3b) for all lots. The HRYs of medium kernels followed the same pattern as observed for MRYS. For superior lots, HRYs of medium kernels were significantly greater than those of unfractioned rice (fig. 3b), while for inferior lots, HRYs of medium kernels were statistically equivalent to those of unfractioned rice (fig. 3b). Likewise for superior lots, HRYs of thick kernels trended 1.0 to 2.5 percentage points greater than those of unfractioned rice (fig. 3b), while for inferior lots HRYs of thick kernels were less than those of unfractioned rice (fig. 3b). Further thickness grading to partition thick kernels to alternate processing streams such as parboiling, could increase HRYs as compared to unfractioned rice (fig. 3b).

Trends for milling yields across the three thickness fractions may be explained by the associated physical properties. For all lots and fractions evaluated, trends of MRY were nearly identical to ρ_b (figs. 3a and 4a). Bulk densities of thin kernels were significantly less than those of medium and thick kernels for all lots evaluated (fig. 4a); likely the result of both more completely filled kernels and greater relative mass of endosperm associated with the medium and thick kernels. Bulk densities of medium and thick kernels were not significantly different for three of the four lots, the exception being Wells-, in which the ρ_b of the thick kernels was significantly greater than that of medium kernels (fig. 4a). For the inferior lots, there was a moderate trend for greater ρ_b of thick kernels compared to

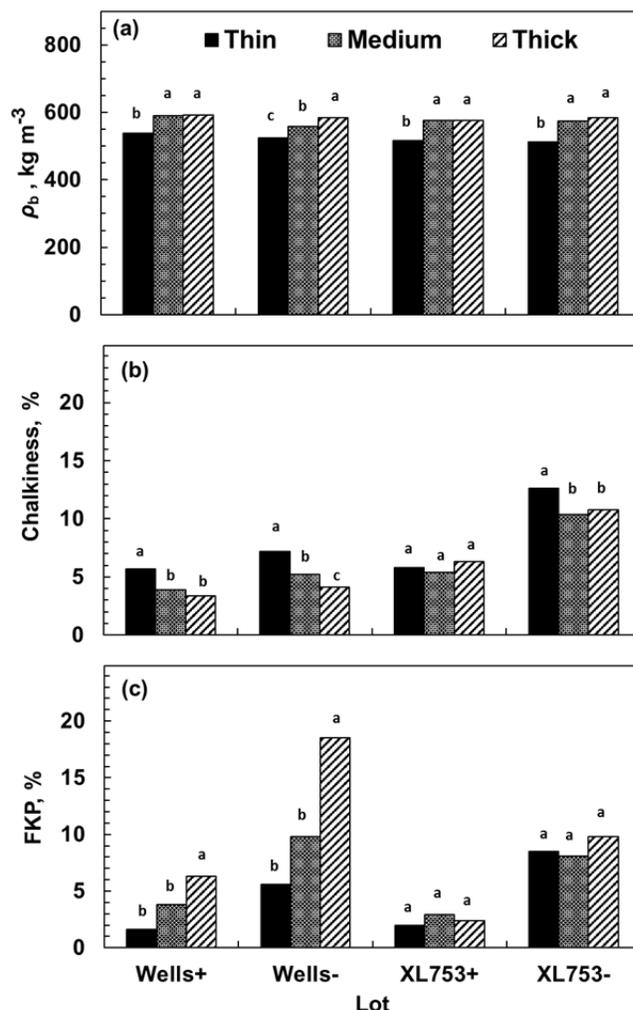


Figure 4. Rough-rice bulk density (ρ_b) (a), brown-rice chalky area (chalkiness) (b), and brown-rice fissured-kernel percentage (FKP) (c) for thickness fractions of four rice lots harvested in 2012, comprising Wells and XL753 cultivars of both superior (+) and inferior (-) milling quality. Thickness grading of rough rice resulted in thin (< 2.00 mm), medium (2.00<<2.05 mm), and thick (>2.05 mm) fractions. Chalkiness is expressed as a percentage of scanned kernel area, and FKP is expressed as a number percentage of fissured kernels. Bars represent the mean of four replicate samples. Within a physical property and lot, values followed by the same letter are not significantly different ($P>0.05$).

thin kernels.

For chalkiness, the overall trend was for reduced chalkiness with increased kernel thickness (fig. 4b), although there were no significant differences in chalkiness between thicknesses of the XL753+ lot (fig. 4b). Chalkiness was greater in thin kernels of the Wells+, Wells-, and XL753- lots when compared to medium and thick kernels (fig. 4b). Comparing medium and thick kernels, significant differences in chalkiness were only observed for the Wells- lot (fig. 4b).

The FKPs varied by cultivar, increasing with increased thickness fraction for both Wells+ and Wells- lots, while no differences were observed between thickness fractions of XL753+ and XL753- lots (fig. 4c). The FKPs for inferior lots of both cultivars tended to be greater than for superior lots (fig. 4c), thereby affecting HRY (fig. 3b). Kernel

fissuring of inferior lots was not related to HMC, although as previously stated, the near-optimal HMC of inferior lots (table 1) did not preclude the possibility of drying and rewetting events before harvest.

With trends in ρ_b mirroring those of MRY, and the potential reduction of MRYs and HRYs resulting from deleterious effects of chalkiness and FKP, a better understanding of the individual and interactive impacts of these physical properties on milling yields were needed. Webb (1985) previously expressed the negative relationship between chalkiness and HRY. However, no reports have detailed the relationships of these physical parameters, either singly or combined, to both MRY and HRY.

Thus, linear regression analysis was conducted to model the impacts of ρ_b , and chalkiness and FKP, on MRY and HRY (table 2). As cultivar and lot were not statistically significant terms for this modeling effort, all lots were grouped; however, only data from thickness graded samples were utilized. Using uni-variate modeling, ρ_b effectively predicted MRY ($R^2=0.91, P<0.0001$), and to a lesser degree HRY ($R^2=0.14, P<0.01$) (table 2). While statistically significant, chalkiness as a uni-variate inadequately predicted MRY ($R^2=0.25, P<0.001$) and HRY ($R^2=0.24, P<0.001$) (table 2). Brown-rice FKP was not significantly related to MRY ($R^2=0.03, P<0.19$) (table 2). However, FKP marginally predicted HRY ($R^2=0.46, P<0.0001$) (table 2). Thus, as previously suggested, the variability in MRY was almost entirely explained by ρ_b , while the variability in HRY was apparently dependent on multiple physical properties.

With the apparent effect of multiple physical properties, in particular for HRY, multi-variate linear regression was also conducted, including all three physical properties as variables (table 2). The predictive equations resulting from multivariate linear modeling are as follows:

$$MRY = 0.10 \times \rho_b - 0.18 \times Chalkiness - 0.01 \times FKP + 13.94 \quad (1)$$

$$HRY = 0.21 \times \rho_b - 1.03 \times Chalkiness - 2.08 \times FKP - 52.90 \quad (2)$$

Table 2. Uni- and multi-variate modeling of the impacts of measured physical properties on milled rice yield (MRY) and head rice yield (HRY).^[a]

Model/Variable	MRY Fit		HRY Fit	
	R ²	P	R ²	P
Uni-variate				
ρ_b	0.91	<0.0001	0.14	<0.01
Chalkiness	0.25	<0.001	0.24	<0.001
FKP	0.03	0.19	0.46	<0.0001
Multi-variate (all variables)	0.93	<0.0001	0.83	<0.0001

^[a] Coefficient of determination (R^2) and statistical significance (P) for uni- and multi-variate linear modeling as affected by rough-rice bulk density (ρ_b), brown-rice chalky area (chalkiness), or brown-rice fissured-kernel percentage (FKP) are presented.

Modeling was conducted for thickness-graded rice (thin, < 2.00 mm; medium, 2.00 << 2.05 mm; thick, > 2.05 mm), across the four lots, comprising Wells and XL753 cultivars of both superior and inferior initial milling quality.

where

MRY = milled rice yield (%)

HRY = head rice yield (%)

ρ_b = bulk density of rough rice (kg m^{-3})

Chalkiness = chalky area of brown rice (% of area)

FKP = fissured-kernel percentage of brown rice (number%).

This multi-variate approach improved R^2 for the prediction of MRY and HRY (table 2). The multi-variate model somewhat improved the prediction of MRY ($R^2=0.93$) compared to that of rough-rice bulk density ($R^2=0.91$), the best uni-variate fit (table 2). However, for HRY the improvement in prediction was considerable, with the multi-variate model effectively predicting HRY ($R^2=0.83$), a considerable improvement over that of FKP, the best uni-variate fit ($R^2=0.46$) (table 2).

The multi-variate linear models for predicting MRY and HRY, developed using thickness-graded data, were then used to predict milling yields of unfractionated rice, with adequate prediction of MRY ($R^2=0.63, P<0.001$) and effective prediction of HRY ($R^2=0.79, P<0.0001$). However, considering the small number of samples (4 lots \times 4 replications), a more robust set of data is warranted to more accurately predict milling yields of unfractionated rice.

CONCLUSIONS

Thickness grading of rough rice resulted in fractions with distinct properties. For all lots, there was a trend of increasing MRY with increasing kernel thickness. Head rice yields did not follow the same trend. While HRYs of medium kernels were greater than those of the thin kernels for all lots, HRYs of thick kernels tended to be less than those of medium kernels, significantly so for the inferior lots of both Wells and XL753 cultivars. Milled rice yield was strongly linked to ρ_b . However, HRYs were linked to multiple physical properties, primarily those of kernel defects such as chalkiness and FKP. The linkages between milling yields and kernel physical properties were confirmed by uni- and multi-variate linear modeling, indicating strong relationships between the measured physical properties – ρ_b , chalkiness, and FKP – and milling yields. Moreover, cultivar was not a statistically significant term for these uni- and multi-variate models; thus, the cultivar variable was removed from the model to focus on physical parameters alone. These easily-measured physical properties could be used to predict the need for thickness grading on a lot-to-lot basis, regardless of cultivar. However, were identity-preservation protocols in place, lot-to-lot designation for specific processing practices such as thickness grading would be simplified. Thickness grading of long-grain rough rice could concentrate chalky and fissured kernels and partition them into alternative processing streams, thereby improving the milling yield of the primary processing stream. However, economic and logistic impacts on commercial milling operations have yet to be considered.

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