PREDICTING MILLING YIELDS OF LONG-GRAIN RICE USING SELECT PHYSICAL PARAMETERS

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ABSTRACT. *Milling yields of long-grain rice were successfully predicted using multi-parameter linear modeling, although the data was limited to lots of only two cultivars (Grigg and Siebenmorgen, 2015). Thus, modeling was expanded to include six currently-produced long-grain cultivars. For unfractioned rice, milling yields [milled rice yield (MRY) and head rice yield (HRY, adjusted to account for degree of milling variations)] were regressed to combinations of physical parameters comprising bulk density (ρb) of rough rice, and fissured-kernel percentage (FKP), chalkiness, and average kernel thickness of brown rice. The resulting models for prediction of milling yields were cross-validated with equivalent data of thickness-fractioned rough rice of the same cultivar lots. Thickness fractions comprised (< 1.7 mm), (1.7 << 1.9 mm), (< 1.9 << 2.0 mm), (2.0 << 2.05 mm), and (> 2.05 mm). Milling yields were first predicted using ρb, FKP, and chalkiness parameters (Model I). The adjusted coefficient of determination (R^2) value indicates that Model I effectively predicted HRY ($R^2 = 0.90$); however prediction of MRY was poor ($R^2 = 0.22$), and related model cross-validations (Valid. $R^2 = 0.67$ and 0.59, MRY and HRY, respectively) were marginal. Adding the kernel thickness parameter in Model II improved milling yield predictions and cross-validations ($R^2 = 0.72$ and 0.94, and Valid. $R^2 = 0.82$ and 0.74, for MRY and HRY, respectively). As the chalkiness parameter estimates in Models I and II were statistically insignificant, Model III considered only the ρb, FKP, and thickness parameters. Model III maintained effectiveness in predictions and cross-validations of milling yields ($R^2 = 0.71$ and 0.95, and Valid. $R^2 = 0.83$ and 0.72, for MRY and HRY respectively). The ρb, FKP, and thickness parameters of Model III effectively predicted MRYs and HRYs of both unfractioned and thickness-fractioned long-grain rice of this set of cultivar lots.*

Keywords. *Bulk density, Chalkiness, Head rice yield, Kernel fissuring, Kernel thickness, Milled rice yield.*

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, 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 layers and germ removed from brown rice during the milling operation. Increased DOM invariably increases the mass removed from rice kernels, thus decreasing MRY (Wadsworth, 1994) and HRY (Sun and Siebenmorgen, 1993; Lanning and Siebenmorgen, 2011). However, Cooper and Siebenmorgen (2007) and Pereira et al. (2008) report that HRYs can be mathematically adjusted to account for variations in DOM.

Grigg and Siebenmorgen (2015) reported that the physical parameters of bulk density, kernel fissuring, and chalkiness impacted milling yields of rice. Grigg and Siebenmorgen (2013, 2015) suggest that milling yields increase with increased bulk density. However, reduced HRYs are associated with kernel fissuring, the result of rapid moisture adsorption by kernels of low moisture content in the field (Lan and Kunze, 1996), or of conditions occurring during post-harvest drying (Schluterman and Siebenmorgen, 2007). Reports of Jindal and Siebenmorgen (1994) and Siebenmorgen et al. (1997) suggest that thicker, bolder kernels are more susceptible to fissuring than thinner kernels.

Chalkiness has also been shown to reduce milling yields (Counce et al., 2005; Lanning et al., 2011), and to negatively impact appearance and marketability of milled rice (USDA-FGIS, 2009; McClung, 2013). 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 is affected by climate during reproductive growth (Counce et al., 2005; Ambardekar et al., 2011; Lanning et al., 2011). Moreover, chalkiness of rice can result from premature harvest (Kocher et al., 1991) or delayed harvest (Mohapatra et al., 1993; Lu et al., 1995; Chen et al., 2008; Espinosa-Mendoza et al., 2012; Grigg et al., 2016).

Kernel thickness also impacts milling yields (Sun and Siebenmorgen, 1993; Jindal and Siebenmorgen, 1994; Grigg and Siebenmorgen, 2013; Grigg and Siebenmorgen, 2015), with increased MRYs and HRYs generally associated with thicker kernels, except where conditions promote kernel fissuring. As the starch accumulates in the rice endosperm, the kernel first attains full length, then full width, and lastly full thickness

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(Lu and Luh, 1991); thus, thin kernels from a cultivar lot likely indicate incompletely filled kernels of lesser structural integrity. Matthews and Spadaro (1976) indicated that breakage of milled rice was greatest in the thinnest fraction, regardless of cultivar. Thickness grading of rough rice prior to milling has been proposed as a means of improving kernel uniformity (Matthews et al., 1982; Chen et al., 1998; Grigg and Siebenmorgen, 2013; Grigg and Siebenmorgen, 2015) and HRYs (Sun and Siebenmorgen, 1993; Jindal and Siebenmorgen, 1994; Grigg and Siebenmorgen, 2013; Grigg and Siebenmorgen, 2015) by removing thin, chalky kernels of rough rice.

Initial modeling of milling yields based on select physical parameters, comprising bulk density, fissured-kernel percentage, and chalky area, were based on data of only two cultivars (Grigg and Siebenmorgen, 2015). The ability to predict milling yields of a wider selection of long-grain cultivars would potentially benefit both rice breeders and processors. Rice breeders commonly measure kernel dimensions and chalkiness in the course of cultivar development (Chang and Li, 1980), and predictive models of milling yields based on such physical parameters could be of particular benefit where quantities of rice are limited. Such predictive models of milling yields could also benefit rice processors in predicting the need for, and outcomes of, thickness grading of rough rice. Thus the previous research was expanded to increase the breadth of cultivar lots and physical parameters evaluated in order to advance models predicting millings yields of long-grain rice.

Materials And Methods

Sample Procurement and Preparation

Seven lots of long-grain rice were obtained, comprising six cultivars (Cheniere, CL151, CL XL745, Roy J, Wells, and XL753). All cultivar lots were considered to be superior in terms of milling yield, with the exception of a single inferior lot of the Wells cultivar (Wells-); the Wells lots (+ and -) were harvested from different locations in 2012. A sufficient quantity of the Wells- was available and was selected simply to represent a low milling yield lot. All cultivar lots were produced using recommended management practices (Hardke, 2013), and were combine harvested at moisture contents (MCs, wet basis) ranging from 13% to 20% in either 2012 or 2013. Except for Cheniere (a cultivar known for consistent milling quality), all selected cultivars ranked highly in terms of planted land area registered in the Arkansas DD50 Rice Management Program (Hardke, 2015).

A dockage tester (Model XT4, Carter-Day, Minneapolis, Minn.) was used to clean each cultivar lot of rough rice, removing dockage and unfilled kernels. The cleaned cultivar lots were conditioned to 12.0±0.5% MC 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). For each cleaned, conditioned cultivar lot, 22 kg of rough rice was stored at 4±1°C prior to use and was equilibrated to room temperature (22±1°C) for at least 24 h prior to further processing.

Thickness Fractioning of Rough Rice

For each cultivar lot, 1 kg of rough rice was reserved as unfractioned (Unf) rice, while 21 kg of rough rice was thickness fractioned 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 by Grigg and Siebenmorgen (2015). 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 physical parameters of the fractions, as well as Unf rice, were determined.

Milling Yields

Four replicate, 150-g samples of conditioned 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 Corp., Hiroshima, Japan) with a roller clearance of 0.048 cm (Siebenmorgen et al., 2006). The resultant brown rice samples were milled (McGill No. 2, RAPSCO, Brookshire, Tex.; 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 (61, Grain Machinery Manuf. Corp., Miami, Fla.). Degree of milling was quantified in terms of surface lipid content (SLC) of head rice (Hogan and Deobald, 1961; Miller et al., 1979; Pomeranz et al., 1975). 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 values reported here were adjusted (HRY) to account for variations in SLC (i.e., DOM) in the manner of Pereira et al. (2008).

Physical Parameters

Bulk density (ρb) of rough rice of each cultivar lot/fraction was determined using a test weight apparatus (Seedburo Equipment Co., Des Plaines, Ill.) as described by Fan et al. (1998). Brown rice properties of each cultivar lot/fraction were determined by first dehulling a 100-g subsample of rough rice as previously described. Any remaining rough rice or broken kernels were then removed prior to subsequent analyses. For each brown rice sample, chalkiness, fissured kernels, and kernel thickness were quantified for 200 intact brown rice kernels. A grain-scope (Model TX-200, Kett Electric Laboratory, Tokyo, Japan) was used to enumerate brown rice kernels having fissures. Fissured-kernel percentage (FKP) was reported as a number percentage of brown rice kernels with one or more fissures. A digital scanning system (WinSeedle Pro 2005a^{TM}, Regent Instruments Inc., Sainte-Foy, Quebec, Canada) was used to determine chalkiness of brown rice (Ambardekar et al., 2011); chalkiness was reported as a percentage of total scanned kernel area. Kernel thickness was quantified using a rice image analyzer (1A, Satake Corp., Hiroshima, Japan), and was reported as the average thickness of the 200 brown rice kernels.

Data Analysis

Statistical software (JMP Pro 12, SAS Institute, Cary, N.C.) was used for analysis of variance (ANOVA, α=0.05) and multi-parameter linear modeling procedures. Means were separated using the Tukey-Kramer Honestly Significant Difference procedure (HSD, $P = 0.05$). Multi-parameter linear regression was used to model milling yields (MRY and HRY) based on associated physical parameter data, and the adjusted (to facilitate comparisons among models with different numbers of parameters) coefficient of determination (R^2) was used to determine the effectiveness of each prospective model. In addition to ρb, FKP, and chalkiness, as reported by Grigg and Siebenmorgen (2015), thickness of brown rice was considered as a potential model parameter.

Models predicting milling yields were developed using data of Unf rice samples (7 lots × 4 replications, n = 28). Models were then cross-validated using milling yields and physical parameters of thickness-fractioned rice (7 lots × 5 fractions × 4 replications, n = 140). Cross-validation consisted of using parameter estimates of each predictive model to calculate predicted milling yields of thickness-fractioned rice, which were then correlated to measured values.

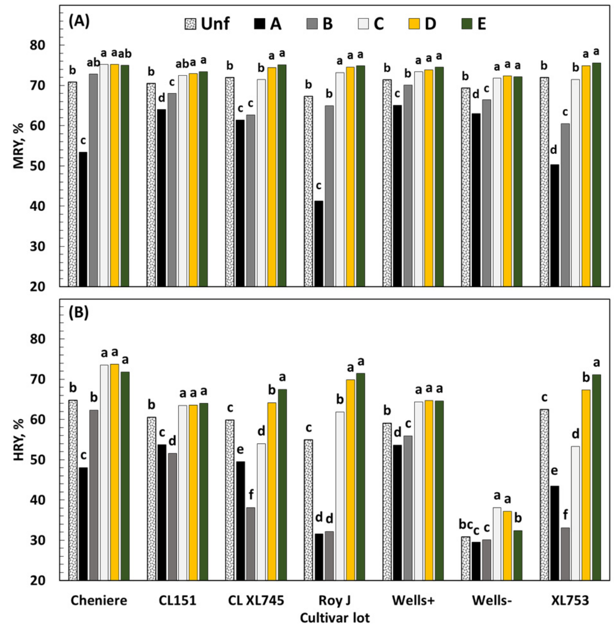

Figure 1. Milled rice yield [MRY] (A) and head rice yield [HRY] (B) of the indicated long-grain rice cultivar lots. Values of HRY were adjusted to 0.4% surface lipid content according to Pereira et al (2008). Unfractioned (Unf) rice and thickness fractions of rice comprising A [< 1.7 mm], B [1.7 << 1.9 mm], C [1.9 << 2.0 mm], D [2.0 << 2.05 mm], and E [> 2.05 mm] were evaluated. Comparisons are valid within a cultivar lot, and column means with a different letter are significantly different (*P<0.05*).

Results and Discussion

Milling Yields

Milled rice yields of the Unf rice ranged from 67% [Roy J] to 72% [CL XL745 and XL753] (fig. 1A). For all cultivar lots, MRYs generally increased as kernel thickness increased when transitioning from the A (thinnest) to the E (thickest) fractions. Differentials between maximum and minimum MRYs of thickness-fractioned rice ranged from 9 percentage points (pp) to 34 pp, with the greatest differentials observed for the Cheniere, Roy J, and XL753 lots. Milled rice yields of the A fraction were significantly less than those of the C, D, and E fractions for all cultivars, and significantly less than the B fraction for all cultivar lots except CL XL745. Milled rice yields of the B fraction were also significantly less than the C, D, and E fractions for all cultivars lots except Cheniere. For the Cheniere, CL151, Roy J, and Wells (+ and -) cultivar lots, MRYs of the C, D, and E fractions were statistically equivalent. Milled rice yields of the C fraction were statistically less than MRYs of the D and E fractions, and greater than MRYs of the B fraction, for the CL XL745 and XL753 cultivar lots. Regardless of cultivar lot, MRYs of the C, D, and E fractions were greater than, or equal to, MRYs of the Unf rice.

Adjusted head rice yields ranged from 30% [Wells-] to 64% [Cheniere] (fig. 1B). The HRYs of the A and B fractions were less than the HRYs of the C, D, and E fractions, regardless of cultivar lot. Differentials between minimum and maximum HRYs of thickness-fractioned rice ranged from 10 to 40 pp, with the greatest differentials observed for the CL XL745, Roy J, and XL753 cultivar lots. For the cultivar lots CL151, CL XL745, Roy J, and XL753, HRYs of the A fraction were significantly greater than, or trended greater than, those of the B fraction. For the Cheniere, CL151, and Wells (+ and -) cultivar lots, HRYs of the C fraction were at least equivalent to HRYs of the D and E fractions. For the CL XL745, Roy J, and XL753 cultivar lots, HRYs consistently increased from C to E fractions. For all cultivar lots, HRYs of the D and E fractions exceeded that of the Unf rice. For the Cheniere, CL151, Roy J, and Wells (+ and -) lots, HRYs of the C fraction also exceeded that of the Unf rice.

Physical Parameters

Bulk densities of the Unf rough rice ranged from 523 [Roy J] to 581 kg m^{-3} [Wells+] (fig. 2A). When considering thickness-fractioned rice, ρbs of the A and B fractions of thickness-fractioned rice trended consistently less compared to the C, D, and E fractions of a given cultivar lot. Bulk densities generally increased with increasing thickness fraction (fig. 2A). Overall trends for ρb were similar to those of milling yields (fig. 1A-B); agreeing with the previous report of the significant relationship between ρb and milling yields (Grigg and Siebenmorgen, 2015).

Fissured-kernel percentages of the Unf brown rice ranged from 0.1% [Cheniere and Roy J] to 24.5% [Wells-], with FKPs of most cultivar lots below 5% (fig. 2B). Trends of FKPs as related to the different thickness fractions varied widely between the cultivar lots. Increased FKPs associated with Unf and thickness-fractioned rice of the Wells- lot appears to be the reason for decreased HRYs associated with this cultivar lot (fig. 1B). Harvest moisture content (HMC) less than optimum of 19% to 22% (wet basis) is often the

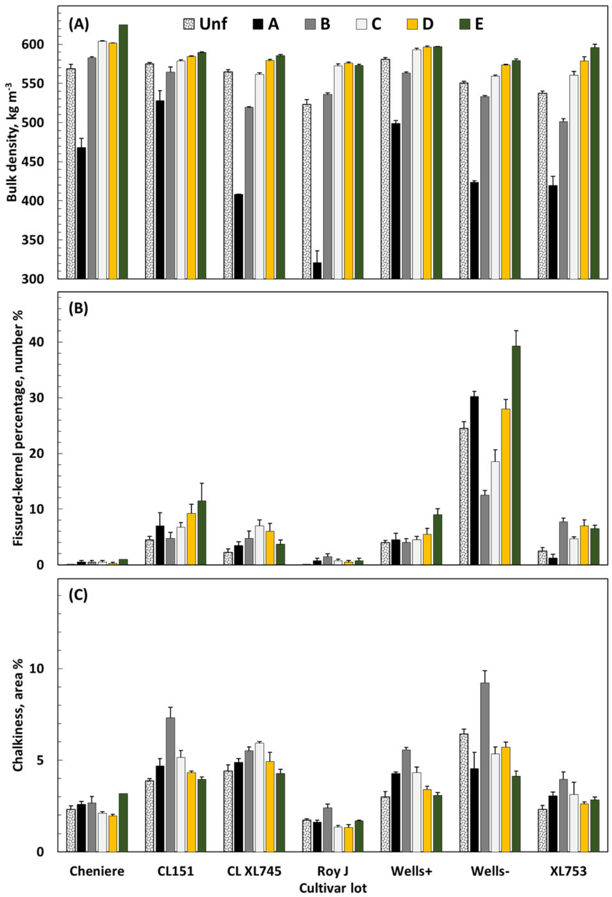

Figure 2. Rough rice bulk density [ρb] (A), fissured-kernel percentage [FKP] (B) and chalkiness of brown rice kernels (C) of the indicated long-grain rice cultivar lots. Unfractioned (Unf) rice and thickness fractions of rice comprising A [< 1.7 mm], B [1.7 << 1.9 mm], C [1.9 << 2.0 mm], D [2.0 << 2.05 mm], and E [> 2.05 mm] were evaluated. Bars indicate the standard error of the column means.

cause of increased kernel fissuring (Siebenmorgen et al., 2007). However, increased FKP values associated with Wells- appear to result from other undocumented environmental factors, as HMC of the Wells- lot (18%) was near optimum, while the HMC of the Wells+ lot (14%) was not. Previous reports indicated increasing FKPs as kernel thickness increased (Jindal and Siebenmorgen, 1994; Siebenmorgen et al., 1997); however, for most of these cultivar lots, FKP trends in relation to kernel thickness fraction were not consistent. Such inconsistencies in FKPs across thickness fractions of cultivar lots were also reported by Grigg and Siebenmorgen (2015). For the Wells- cultivar lot in particular, the FKP of the A fraction was considerably greater than expected.

Chalkiness of the Unf brown rice ranged from 1.7% [Roy J] to 6.4% [Wells-] (fig. 2C). Regardless of cultivar lot, chalkiness was generally greatest in the B fraction. The A and B fractions would likely retain the majority of the late-developing, thin, and chalky kernels described by Mohapatra et al. (1993). Chalkiness generally declined as thickness increased from the B to E fraction.

Kernel thickness of the Unf brown rice ranged from 1.6 [Roy J] to 1.9 mm [XL753] (fig. 3). Considering thickness-fractioned rice, kernel thickness consistently increased with increasing thickness from the B to E fraction, regardless of cultivar lot. However, for all cultivar lots, there was a trend for greater kernel thickness of the A fraction compared to the B fraction. This trend was possibly caused by brown rice observed in the rough rice prior to thickness fractioning, the result of combine harvesting; these brown-rice kernels most likely passed through to the thinnest A fraction upon thickness fractioning, resulting in increased average kernel thickness of brown rice in comparison to the B fraction (fig. 3). Moreover, in comparison to the B fraction, the presence of these thicker kernels within the A fraction could account for unexpected trends of increased HRYs [CL151, CL XL745, Roy J, and XL753 cultivar lots] (fig. 1B), increased FKPs [CL151, Wells+, and Wells- cultivar lots] (fig. 2B), and decreased chalkiness [CL151, CL XL745, Roy J, Wells (+ and -), and XL753 cultivar lots] (fig. 2C). Limited lot quantities precluded further thickness fractioning and quantification of brown rice within the resulting thickness fractions in retrospect; however, the potential impacts of such brown rice on measured physical parameters should be considered in future studies of thickness fractioning of combine-harvested rice.

Multi-Parameter Linear Modeling

Milling yields were regressed to corresponding physical parameters (ρb, FKP, chalkiness, and thickness) of the Unf cultivar lots, and the resulting predictive equations were cross-validated using equivalent data (milling yields, ρb, FKP, chalkiness, and thickness) of thickness-fractioned rice of the same cultivar lots. This was a modification of the approach of Grigg and Siebenmorgen (2015), where milling yields of thickness-fractioned rice were regressed to corresponding physical parameters (ρb, FKP, and chalkiness), and validated using equivalent data of Unf rice. The change in approach reflects the likelihood that potential improvements in commercial milling yields by first thickness grading, would be inferred from unfractioned rice lots. Rice breeders would also likely be interested in milling yields of

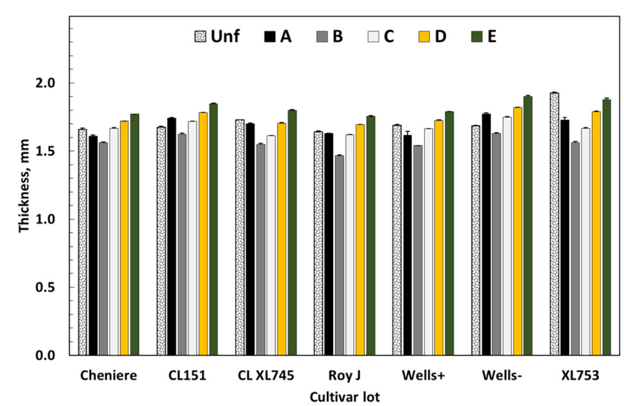

Figure 3. Brown rice kernel thickness of the indicated long-grain rice cultivar lots. Unfractioned (Unf) rice and thickness fractions of rice comprising A [< 1.7 mm], B [1.7 << 1.9 mm], C [1.9 << 2.0 mm], D [2.0 << 2.05 mm], and E [> 2.05 mm] were evaluated. Bars indicate the standard error of the column means.

unfractioned rice; moreover, samples of rice cultivars in development are often of small size, precluding thickness grading prior to determination of physical properties.

For each resulting predictive model, statistics comprised of the variance inflation factor (VIF), parameter estimates, the statistical significance (*P*), and adjusted coefficient of determination of both the model (R^2) and the cross-validation (Valid. R^2) were reported. The VIF statistic was used as an indicator of parameter multicollinearity; with values of approximately 1 indicating no multicollinearity, and increasing potential of multicollinearity as VIF values increase (1 < VIF < 5) (Klimberg and McCullough, 2013). When VIF values exceeded 5, multicollinearity between one or more parameters was assumed (Klimberg and McCullough, 2013). Along with *P*, VIF was considered in decisions to maintain or remove parameters.

Model I: Bulk Density (ρb), Fissured-Kernel Percentage (FKP), and Chalkiness

Milling yields were first regressed to the physical parameters ρb, FKP, and chalkiness (Model I), those originally considered by Grigg and Siebenmorgen (2015) (table 1). For Model I parameter estimates, VIF < 5 for all parameter estimates; however, VIFs of the FKP and chalkiness parameters approached 5, suggesting the potential of multicollinearity between parameter estimates. Only the ρb estimate was statistically significant ($P < 0.05$) in the Model I prediction of MRYs. The prediction of MRYs by Model I was inadequate ($R^2 = 0.22$), although Model I cross-validation of thickness-fractioned MRYs was marginal (Valid. $R^2 = 0.65$).

Model I resulted in effective prediction of HRYs ($R^2 = 0.90$), with statistically significant ρb and FKP parameter estimates. However, the Model I cross-validation of thickness-fractioned HRYs was marginal (Valid. $R^2 = 0.61$). Thus, the use of only ρb, FKP, and chalkiness of Model I was not appropriate for this set of cultivar lots/thickness fractions.

Model II: Bulk Density (ρb), Fissured-Kernel Percentage (FKP), Chalkiness, and Thickness

As Model I was largely ineffective, kernel thickness of brown rice was considered as an additional physical parameter in Model II. As with parameter estimates of Model I, VIF < 5 for all parameter estimates, with VIFs of the FKP and chalkiness parameters remaining near 5. Prediction of MRYs of Unf rice using Model II physical parameters was effective ($R^2 = 0.72$), as was cross-validation with data of thickness-fractioned rice (Valid. $R^2 = 0.82$).

Prediction of HRYs using Model II physical parameters ($R^2 = 0.94$), and model cross-validation with data of thickness-fractioned rice (Valid. $R^2 = 0.74$) were effective. The statistical significance of the thickness parameter estimate ($P \leq 0.0001$, for both MRY and HRY) was of note in Model II, as this model was developed with data of Unf rice, rather than thickness-fractioned rice.

While chalkiness was a statistically significant parameter in previous modeling of milling yields (Grigg and Siebenmorgen, 2015), the chalkiness parameter was statistically insignificant in prediction of MRYs and HRYs of these cultivar lots using Models I and II. Moreover, VIF values of the chalkiness parameter estimate of Models I and II suggest

Table 1. Multi-parameter linear regression of indicated physical parameters to predict milled rice yield (MRY) and adjusted head rice yield (HRY[a]) of long-grain rice[b].

		MRY		HRY	
Parameter[c]	VIF[d]	Estimate	*P*	Estimate	*P*
Model I					
Intercept	-	52.315	<0.0001	-3.106	0.8675
ρb	1.22	0.031	0.0431	0.120	0.0019
FKP	3.91	-0.096	0.1683	-1.156	<0.0001
Chalkiness	4.07	0.371	0.3076	-0.425	0.6176
		$R^2 = 0.22$ *Valid. $R^2 = 0.65$*		$R^2 = 0.90$ *Valid. $R^2 = 0.61$*	
Model II					
Intercept	-	21.552	0.003	-65.044	0.0023
ρb	1.32	0.048	<0.0001	0.153	<0.0001
FKP	3.94	-0.072	0.085	-1.109	<0.0001
Chalkiness	4.07	0.313	0.1506	-0.541	0.3896
Thickness	1.10	12.636	<0.0001	25.441	0.0001
		$R^2 = 0.72$ *Valid. $R^2 = 0.82$*		$R^2 = 0.94$ *Valid. $R^2 = 0.74$*	
Model III					
Intercept	-	19.057	0.0067	-60.734	0.0028
ρb	1.09	0.053	<0.0001	0.143	<0.0001
FKP	1.01	-0.021	0.3286	-1.197	<0.0001
Thickness	1.09	12.748	<0.0001	25.246	0.0001
		$R^2 = 0.71$ *Valid. $R^2 = 0.83$*		$R^2 = 0.95$ *Valid. $R^2 = 0.72$*	

[a] HRY values were adjusted to 0.4% surface lipid content according to the method of Periera et al (2008).

[b] Cultivar lots comprised Cheniere, CL151, CL XL745, Roy J, Wells (both superior (+) and inferior (-) HRYs), and XL753.

[c] Model parameters comprised bulk density of rough rice (ρb), and fissured-kernel percentage (FKP, number percentage), chalkiness (area percentage), and the average kernel thickness of brown rice.

[d] Variance inflation factor (VIF), parameter estimate (Estimate), statistical significance (*P*), mean square error of the model (MSE), adjusted coefficient of determination of the regression model (R^2) using data of unfractioned rice, and the cross-validation of the regression model (Valid. R^2) using data of thickness-fractioned rice.

a strong potential for multicollinearity with other parameter estimates. Considering the statistical insignificance ($P > 0.05$) and VIF values of chalkiness, this parameter was excluded from Model III. The FKP parameter was not statistically significant in prediction of MRYs using Models I and II. However, the FKP parameter was highly significant in prediction of HRYs; thus, the FKP parameter was retained with Model III.

Model III: Bulk Density (ρb), Fissured-Kernel Percentage (FKP), and Thickness

Using only the physical parameters ρb, FKP, and thickness, Model III effectively predicted milling yields of both unfractioned rice and thickness-fractioned rice, as indicated by R^2 and Valid. R^2 values (table 1). While parameter estimates, R^2, and Valid. R^2 values were essentially unchanged from those of Model II, removal of the chalkiness parameter greatly reduced VIF values of Model III; such that VIFs were approximately 1, indicating no multicollinearity. For these data, Model III appears to be the best overall model for prediction of both MRYs and HRYs. However, chalkiness has been shown to be significantly related to milling yields of long-grain rice cultivars (Grigg and Siebenmorgen, 2015), and chalkiness is impacted by both environmental conditions (Counce et al., 2005; Ambardekar et al., 2011; Lanning et al., 2011) and harvest scheduling (Mohapatra et al., 1993; Lu et al., 1995; Chen et al., 2008; Espinosa-Mendoza et al., 2012; Grigg et al., 2016). While not retained in Model III, it may be necessary to consider the the chalkiness parameter in further refinement of these modeling efforts, particularly if utilizing data of rice lots grown in multiple regions and under different environmental, production, and harvest conditions.

Conclusions

Model I, comprising ρb, FKP, and chalkiness parameters and previously reported by Grigg and Siebenmorgen (2015), was largely ineffective in predicting milling yields of this broader selection of cultivar lots. However, addition of the brown rice kernel thickness parameter (Model II) resulted in effective prediction of MRYs and HRYs of unfractioned and thickness-fractioned rice. Removal of the chalkiness parameter (Model III) preserved the effectiveness in predicting milling yields, while negating multicollinearity among the retained physical parameters.

In the event that the primary utility of these models is determination of MRY, the FKP parameter could likely be excluded from the resultant predictive model; thus, considerably reducing the time and effort currently required to collect FKP data. However for the cultivar lots evaluated here, the FKP parameter was important in predicting HRY. While still utilizing data limited to cultivars commonly produced in Arkansas, results indicate that Model III can effectively predict milling yields of unfractioned and thickness-fractioned long-grain rice. Thus, such multi-parameter linear modeling could be used to predict milling yields of both small samples associated with rice breeding programs, and large lots associated with rice processing facilities.

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