ABSTRACT. Head rice yield is an important index of rice quality. The official procedure for determining head rice yield requires a 1000-g sample of rough rice or a lesser sample of rough rice for a modified procedure. In certain situations, such amounts of rough rice may not be available for conducting an actual milling analysis; thus, there is a need to provide alternative methods of estimating head rice yield using a smaller sample. In this study, a PaddyCheck instrument was used to individually measure the three-point bending strength of approximately 250 rough rice kernels per sample. The instrument then classified the kernels as either “hard,” “soft,” or “broken by a force <17 N” (BBF). Additionally, each kernel was individually illuminated using polarized light as a means of estimating chalkiness. The kernel parameters measured using the PaddyCheck were then used to develop an equation for estimating head rice yield, based upon head rice yields determined using a modified milling procedure. The equation developed could be used in conjunction with the PaddyCheck instrument to provide estimates of head rice yield and thus, might allow the instrument to be more useful to practitioners in breeding programs and others involved in harvesting and drying operations to compare head rice yields of various samples/treatments, where the available rough rice sample or time is not sufficient to conduct an actual milling analysis.

Keywords. Breaking force, Head rice yield, PaddyCheck, Rice milling, Rice quality, Rough rice.

Head rice yield (HRY) is one of the important quality indices used to quantify the commercial value of rice. Head rice yield is defined as the mass percentage of rough rice kernels that remain as at least three-fourths of the length of an intact kernel after milling (USDA, 2009). The remaining kernel fragments from the milling operation are referred to as brokens, and have a reduced commercial value, typically 60% to 80% of the value of head rice (Siebenmorgen et al., 2008).

Multiple researchers have made efforts to improve HRYs through breeding programs (Gravois, 1998; Brar et al., 2012), optimization of harvesting (Fan et al., 2007; Siebenmorgen et al., 2007; Bautista et al., 2009), and drying operations (Cnossen and Siebenmorgen, 2000; Fan et al., 2007; Schluterman and Siebenmorgen, 2007). In these studies, HRY was quantified using a laboratory mill. The official USDA test method for determining HRY requires a 1000-g sample of rough rice, which is milled using a McGill No. 3 mill (USDA, 2009). Most research and industry laboratories use a modification of the official test method, using a lesser sample of rough rice milled using a McGill No. 2 mill. Pomeranz and Webb (1985) indicated that the amount of rice sample, time required, and cost associated with milling limit the usefulness of standard milling procedures in screening large numbers of samples in the early stages of plant breeding programs.

Kernel strength has been proposed to be an attribute that may be used in estimating HRY. Lu and Siebenmorgen (1995) correlated HRY to breaking strength of rough rice kernels and concluded that the percentage of intact kernels after milling was positively correlated to the percentage of rough rice kernels that withstood a breaking force of 15 N in bending. Siebenmorgen and Qin (2005) and Siebenmorgen et al. (2005) made similar observations wherein HRY was shown to be correlated with the percentage of brown rice kernels that withstood a 20 N force in a three-point bending test. Low kernel breaking forces are typically associated with immature (high-MC) and thin kernels, fissured kernels, and/or chalky kernels; all of these are generally known to be mechanically weaker and more susceptible to breakage during milling (Bamrungwong et al., 1988; Siebenmorgen and Qin, 2005).

Based on the findings of Lu and Siebenmorgen (1995), Siebenmorgen and Qin (2005), and Siebenmorgen et al. (2005), the PaddyCheck instrument (Perten Instruments, Hägersten, Sweden) was developed. This instrument automatically conducts a three-point bending test on individual rough rice kernels, applying a force of up to 17 N per kernel. Kernels that can withstand a 17-N force in bending are classified as “hard” (strong kernels) whereas kernels that cannot
withstand the force are classified as “broken by force” (weak kernels) (Purhagen et al., 2018). Thus, the PaddyCheck instrument tallies the number of strong and weak kernels, which could subsequently be used as the basis for estimating HRY. The instrument also provides an estimate of translucency of each kernel. The objective of this study was to develop and then validate a regression model for estimating HRY using PaddyCheck breaking force and translucency information.

**MATERIALS AND METHODS**

**MILLING ANALYSES**

Thirty-four long-grain rough rice samples, comprising pureline and hybrid cultivars, were received from the Federal Grain Inspection Service (FGIS) in Stuttgart, Arkansas. The HRY of each of the 34 samples had been measured using a McGill No. 3 mill (McGill No. 3, RAPSCO, Brookshire, Tex.) according to the official FGIS procedure for HRY analysis (USDA, 2009). To determine how the McGill No. 2 mill compares to the McGill No. 3 mill for HRY analysis, milling analyses were conducted with a McGill No. 2 mill on sub-samples from each of the 34 rough rice samples. Thus, a 150-g sub-sample of each rough rice sample from the FGIS was dehulled using a laboratory sheller (THU 35B, Satake Corp., Hiroshima, Japan) with a roller clearance of 0.48 mm (Siebenmorgen et al., 2006). The resulting brown rice was milled for 30 s using a laboratory mill (McGill No. 2, RAPSCO, Brookshire, Tex.) with a 1500-g mass placed on the lever arm 150 mm from the centerline of the milling chamber. Head rice was then separated from broken kernels using a shaker table (Grain Machinery Mfg. Co., Miami, Fla.).

**PADDYCHECK MEASUREMENTS**

Approximately 250 rough rice kernels from each of the 34 samples were analyzed using a PaddyCheck instrument fitted with a singulator disc of cavity size 11 × 3.5 mm. The PaddyCheck output files were saved on a flash drive and transferred to a computer equipped with Perten Singulator Plus Software ver. 1.06.343.0 (Perten Instruments, Hägersten, Sweden). The Perten software provides a more elaborate data output than what is displayed by the PaddyCheck instrument. Data obtained from the software included the number of kernels that were classified as: hard kernels, kernels broken by force (BBF), and soft kernels as shown in figure 1. Additionally, each kernel was individually illuminated using polarized light within the PaddyCheck to estimate kernel translucency, which was then expressed using polarized light within the PaddyCheck to estimate kernel translucency, which was then expressed in Perten Translucency Units (PTU). The PaddyCheck instrument was used as predictor variables in developing linear regression models for estimating HRY.

**STATISTICAL ANALYSIS**

Data analyses were conducted using a statistical package (JMP® Pro 14.0.0, SAS Institute Inc., Cary, N.C.). Regression models were developed using a stepwise regression method with the ‘all possible models’ option and the heredity restriction option selected. Selection of the best fitting models was then conducted by assessing the Akaike’s Information Criterion (AICc) (Sugiura, 1978), adjusted R², and root mean square error (RMSE).

**RESULTS AND DISCUSSION**

Head rice yields determined using the McGill No. 2 mill were compared to HRY’s determined using the official FGIS procedure (McGill No. 3 mill) as shown in figure 2. The two procedures were shown to have a strong degree of similarity in determining HRYs of long-grain rice samples. The McGill No. 2 and McGill No. 3 mills produced comparable HRYs, and thus, regression models were developed based upon HRYs determined using a McGill No. 2 mill, since the McGill No. 2 mill is more commonly used in the rice industry than the McGill No. 3 mill.

Pearson’s correlation coefficients were computed between all pairs of variables measured using the PaddyCheck instrument (table 1). Pairs of variables that produced Pearson’s correlation coefficients (r) close to 1 were an indication of collinearity between these variables. As shown in table 1, hard kernels and BBF kernels had a correlation of -0.99, an indication that as the number of BBF kernels increased, the number of hard kernels decreased, thus the two variables are collinear, although inversely so. Collinearity between pairs of predictor variables can result in data redundancy that distorts the overall fitted model and as such, the variable ‘BBF kernels’ was deleted as a predictor to address the collinearity issue. Therefore, ‘BBF kernels’ was not used as a variable in developing HRY estimation models.

Linear relationship graphs between variables (hard, soft, and high-PTU kernels) measured using the PaddyCheck instrument and HRY determined using the modified procedure (McGill No. 2 mill) were plotted to determine how each variable affected HRY. Two data points were identified as outliers and were excluded from the analysis. Figure 3 shows plots between all pairs of variables measured using the PaddyCheck instrument. Pairs of variables that produced Pearson’s correlation coefficients (r) close to 1 were an indication of collinearity between these variables. As shown in table 1, hard kernels and BBF kernels had a correlation of -0.99, an indication that as the number of BBF kernels increased, the number of hard kernels decreased, thus the two variables are collinear, although inversely so. Collinearity between pairs of predictor variables can result in data redundancy that distorts the overall fitted model and as such, the variable ‘BBF kernels’ was deleted as a predictor to address the collinearity issue. Therefore, ‘BBF kernels’ was not used as a variable in developing HRY estimation models.

To identify variables that are individually or in combination good predictors of HRY, the variables: hard kernels, soft kernels, high PTU kernels, and the interactions thereof to the 2nd degree were used to develop 15 models with each model having up to six terms. From the 15 models, the best four models were identified using statistical indices and were evaluated further as shown in table 2. Model adequacy evaluations were based on identifying the model with the least number of variables, the greatest adjusted R², and the least AICc and RMSE. Using the above-mentioned model selection criteria, model 1 (eq. 1) was shown to be the most adequate for estimating HRY for a minimum of 250 kernels with a proportion of hard kernels of between 53.2% and 90.4%.
Estimated \( \text{HRY} = -43.4452 + 1.2147 \times \text{hard kernels}, \% \) (1)

As shown in table 2, model 1 had an adjusted \( R^2 \) of 0.93, an AICc of 174.30, which was the least among the four models, and a RMSE of 3.42. Model 1 had one variable (hard kernels). Hard kernels are the strong kernels, which withstood a 17 N force in bending (Purhagen et al., 2018). Results from this study confirm the findings of Lu and Siebenmorgen (1995), Siebenmorgen and Qin (2005), and

Table 1. Pearson’s correlation coefficients between pairs of variables measured using the PaddyCheck instrument.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hard Kernels</th>
<th>Soft Kernels</th>
<th>BBF [a] Kernels</th>
<th>High PTU [b] Kernels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard kernels</td>
<td>1</td>
<td>-0.57</td>
<td>-0.99</td>
<td>0.54</td>
</tr>
<tr>
<td>Soft kernels</td>
<td>1</td>
<td>1</td>
<td>0.47</td>
<td>-0.20</td>
</tr>
<tr>
<td>BBF kernels</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-0.55</td>
</tr>
<tr>
<td>High PTU kernels</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

\[a\] BBF – Broken by a force less than 17 N.

\[b\] PTU – Perten Translucency Unit.
Siebenmorgen et al. (2005) wherein, highly significant correlations were reported between the proportion of strong kernels in a sample and the sample HRY determined using a McGill No. 2 mill.

Validation of the estimation ability of model 1 (eq. 1) was conducted using a new data set that was generated by milling 55 rough rice samples using a McGill No. 2 mill to determine HRY. Approximately 250 rough rice kernels from each sample were analyzed using the PaddyCheck instrument and the variable percentage of hard kernels input into equation 1 to estimate HRY. The measured HRY was then plotted against the estimated HRY (fig. 4). Model 1 was shown to adequately estimate HRY determined using the McGill No. 2 mill. As shown in figure 4, the estimated and measured HRY values were highly correlated with a coefficient of determination of 0.93, a Pearson’s correlation coefficient of 0.96, and an RMSE of 3.48. These results show an adequate HRY estimation ability of the developed model.

**CONCLUSIONS**

Head rice yields determined using a McGill No. 2 mill were strongly correlated to those determined with a McGill No. 3 mill, an indication that the two milling procedures produce similar HRY values. The percentage of hard (strong) kernels, soft kernels, and high PTU kernels in a rough rice sample determined using the PaddyCheck instrument were each linearly related to HRY determined using the McGill No. 2 mill. However, model 1 (Estimated HRY = –43.4452 + 1.2147 × Hard kernels, %) was shown to be the most adequate model for estimating HRYs determined using the McGill No. 2 mill. This equation could be used in conjunction with the PaddyCheck instrument to provide estimates of HRY and thus, might allow the instrument to be more useful in estimating the milling yields of rice, thus allowing personnel in breeding programs and others involved in harvesting and drying operations to evaluate and compare the HRYs of various samples or the effect of treatments, especially in situations where the available rough rice sample or time is not sufficient to conduct an actual milling analysis.

**ACKNOWLEDGEMENTS**

The authors acknowledge the financial support by the corporate sponsors of the University of Arkansas Rice Processing Program and the Arkansas Rice Research and Promotion Board. Special thanks go to the Federal Grain Inspection Service in Stuttgart, Arkansas, for providing rice samples used in this study.

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