Factors Affecting the Slope of Head Rice Yield vs. Degree of Milling

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ABSTRACT

Milling data of four long-grain rice cultivars were analyzed to determine the uniformity in the slope of their curves for head rice yield (HRY) versus the corresponding degree of milling (DOM). The data set for each cultivar comprised samples that had been subjected to various drying air conditions and durations and milled over a range of moisture contents. All treatment combinations were split and milled for either 15, 30, 45, or 60 sec in a McGill no. 2 laboratory mill to obtain HRY versus DOM data. Linear relationships between HRY and DOM, as observed in past research, were confirmed. This implies that as rice is milled to greater extents (higher DOM), the HRY decreases linearly. Within the bounds of the experimental levels tested, neither the drying air condition nor drying duration affected the rate at which HRY changed with DOM. However, the cultivar and the moisture content at which the rice was milled significantly ($P < 0.05$) influenced this rate. At higher milling moisture contents, the decrease in HRY per unit of increase in the DOM was greater than at lower moisture contents. While not conclusive, there was an indication of a relationship between the average kernel thickness of a cultivar and the HRY versus DOM slope.

A goal of rough rice processing is to achieve an intact, well-milled final product; however, several processing operations influence milling benchmarks. After harvest, the rough rice is dried to ≈12–13% moisture content (MC), wet basis. This dried product is then hulled and milled. Rice quality is most commonly summarized in terms of the head rice yield (HRY) and milled rice yield (MRY). The HRY is the mass percentage of rough rice remaining after complete milling. Head rice is defined as kernels three-fourths or more of the original kernel length (USDA 1979). Similarly, the MRY is the mass percentage of rough rice remaining as milled rice, which includes both head rice and broken kernels.

The degree of milling (DOM) is the extent to which the bran layers are removed by the milling operation. The Federal Grain Inspection Service classifies samples into one of four DOM levels (well-milled, reasonably well-milled, lightly milled, or undermilled) using visual comparison to standard samples representing each level. A more accurate, elaborate, and time-consuming method of estimating DOM is by measuring the amount of surface fat remaining on kernels through petroleum ether extraction (Hogan and Deobald 1961, Watson et al 1975). Bhashyam and Srinivas (1984) quantified DOM in terms of degree of polish by measuring whiteness using a photovoltaic reflectance meter. Recently introduced commercial instruments provide rapid estimates of DOM through transmittance and reflectance measurements. Siebenmorgen and Sun (1994) established a linear relationship between DOM readings from the MM1-B milling meter (Satake Engineering Co., Ltd., Tokyo, Japan) and surface fat concentration for each of three cultivars of long-grain rice.

Milling influences the values of MRY, HRY, and DOM. The removal of bran layers as milling duration increases results in the reduction of MRY and HRY and an increase in DOM (Andrews et al 1992). Bhashyam and Srinivas (1984) noted that a 2% increase in degree of polish affected a 4% increase in breakage. Sun and Siebenmorgen (1993) established linear relationships between HRY and DOM for samples milled in a McGill no. 2 laboratory mill. Archer et al (1994) showed that drying treatment did not significantly affect the HRY versus DOM slope for a given cultivar harvested at a given MC. Separate slopes were reported for each cultivar-harvest MC combination.

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Several authors have documented the effect of MC at milling on HRY and DOM (Wasserman 1960, 1961; Pominski et al 1961; Webb and Calderwood 1977; Banaszek et al 1989). Banaszek et al (1989) showed that, as MC decreased, HRY increased when samples were milled for a constant duration using a McGill no. 2 laboratory mill. Within the MC range in which rice was classified as being well-milled, MC accounted for more than 10 percentage points of change in HRY.

The operation of the McGill no. 2 laboratory mill has been shown to affect milling results. Velupillai and Pandey (1987) showed a dependence of the DOM on milling time by milling samples for periods of 0–60 sec in 5-sec increments. By increasing the pressure settings on the mill, Webb and Calderwood (1977) demonstrated that varying pressure settings can be used to obtain an equivalent DOM.

Sun and Siebenmorgen (1993) showed that DOM and HRY were linearly related. This correlation has been used by Sun and Siebenmorgen and other researchers to compare HRY values at a common DOM level. Milling of samples for a constant duration yields similar results. However, correction to a standard DOM level further reduces variability in HRY measurement. As part of a study evaluating the effects of brown rice temperature on milling outcomes, Archer and Siebenmorgen (1995) illustrated the importance of adjusting HRY to a common DOM level. Observed differences in HRY, caused by reducing brown rice temperature, were removed by correcting HRY to a common DOM.

Slope uniformity across drying conditions, cultivars, and milling MC levels was evaluated in this study. If these factors can be eliminated or the effects characterized, then the procedure for adjusting HRY to a common DOM could be greatly simplified and more readily incorporated as part of a standard routine for laboratory HRY determination.

MATERIALS AND METHODS

Rough rice samples were processed across a typical range of commercial processing conditions. Laboratory methods were used to simulate the commercial unit operations of cleaning, drying, conditioning, and milling. All samples were cleaned and conditioned identically, but drying and milling conditions varied. The experimental design incorporated drying air conditions representative of those used in both on-farm bins and commercial column dryers. The resulting samples were milled for various durations to produce a range of DOM, MRY, and HRY values.

Sample Procurement

Drying tests were performed using five cultivar-harvest MC combinations of long-grain rice. The cultivar-harvest MC combinations used were: Alan-23%, Alan-19%, Lacassine-21%, Newbonnet-19%, and Millie-21%. The rice was grown in 1993 at the University of Arkansas Rice Research and Extension Center at Stuttgart, AR. Immediately after harvest, foreign matter was removed with a Carter-Day dockage tester. No. 28, 25, and 22 sieves were used in the top, middle, and bottom sieve carriages, respectively.

Drying Procedure

Drying tests were started the day of, or the day following, harvest. Samples were dried by circulating conditioned air through perforated trays in one of two 16-tray conditioning chambers. The trays were 152 × 254 mm (6 × 10 in.) and were configured in a parallel drying arrangement. A relative humidity and temperature control unit, the 8.5 m^3/min (300 ft^3/min) Climate-Lab-AA, (Parameter Generation and Control, Inc., Black Mountain, NC) coupled to each chamber provided conditioned air for all tests. Air from the control unit flowed into a plenum beneath the trays, passed through the samples to permit drying, and then returned to the control unit to form a closed loop system. The air temperature and relative humidity inside the chamber were monitored by a dew point hygrometer.

Four drying air conditions involving relative humidity and temperature produced varying drying rates and HRY effects. Figure 1 is a psychrometric representation of the selected conditions. Points A and B represent air conditions corresponding to an equilibrium moisture content (EMC) of 8.6%, and points C and D correspond to an EMC of 6.3% as estimated using the Chung equation (ASAE 1995). The rationale for selection of these particular conditions was to investigate basic drying rate-HRY responses and was presented by Schulman et al (1993).

For each drying test, a 550-g sample of rough rice was placed into each of the 16 trays for up to 4 hr of drying. The initial depth of rice in any tray was ≈15 mm. Two samples were removed at each 15-min interval up to 1 hr and at each 1-hr interval up to 4 hr. The drying rates and HRY reduction were reported by Schulman et al (1993). The two samples removed after every drying duration were combined to provide sufficient rice for the milling procedure. After removal from the drying chamber, the samples were allowed to slowly dry (i.e., over a period of four to six days) to ≈12.5% MC in another conditioning chamber. Another control unit (Parameter Generation and Control, Inc.) provided this chamber with air at 33.0°C and 67.8% rh; air conditions corresponded to an EMC of 12.5% as calculated by the Chung equation (ASAE 1995). The 12.5% samples were then placed in sealed plastic bags and stored at 1°C for approximately three months until milling. Representative MC values at the time of milling are given in Fig. 2.

A replicate drying test was conducted immediately after the first 4-hr test was completed. The total number of samples dried was 320 (five cultivar per harvest-MC combinations × four drying air conditions × eight drying durations × two replicates).

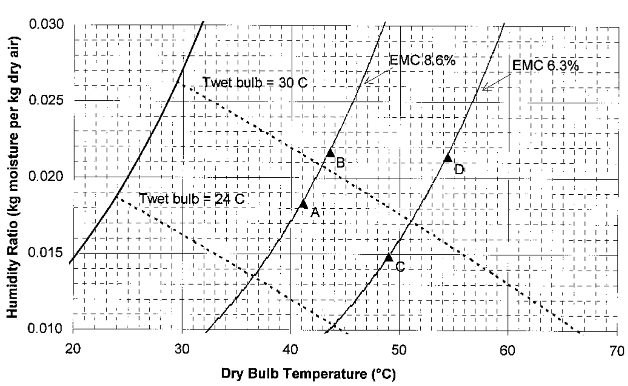

Fig. 1. Psychrometric representation of four (A–D) drying conditions. Equilibrium moisture contents (EMC) were calculated according to the Chung equation (ASAE 1995).

Milling Procedure

Rough rice samples conditioned to 12.5% MC were removed from cold storage and allowed to warm to room temperature. MC of individual rough rice samples were measured with a moisture meter (Motomco model 919A, Dickey-john Corp., Auburn, IL). From each of the 320 samples, four 150-g rough rice subsamples were hulled in a McGill laboratory huller with a clearance of 0.048 cm (0.019 in.) between the rollers (USDA 1982). The brown rice was then milled in a McGill no. 2 mill equipped with an automatic timer. A 1,500-g mass was placed on the mill lever arm 15 cm from the center of the milling chamber. The four subsamples were milled for either 15, 30, 45, or 60 sec to produce varying MRY, HRY, and DOM values. Brokens were removed from the resulting white rice in a Seedboro sizing device (with 5.16-mm holes in the plate).

DOM Determination

DOM of the head rice was measured using a milling meter, Satake model MM1-B. The milling meter displays DOM as a value from 0 (for brown rice) to 199 (for pure white rice). Therefore, the larger the DOM number, the more well-milled the sample. DOM levels of 85–95 are target levels for most commercial rice mills. Three DOM readings, the average of which was calculated and displayed by the meter, were taken on a subsample of ≈25 g. This procedure was repeated for a second subsample, and the mean of the two DOM values was reported as the DOM for the sample.

Size Fractionation

To characterize the kernel size of each rice cultivar, every cultivar-harvest MC combination was separated into thickness fractions, a method similar to that of Sun and Siebenmorgen (1993). Approximately 500 g of rough rice for every cultivar-harvest MC combination was removed from cold storage. All samples had previously been cleaned with the Carter-Day dockage tester and equilibrated to 12.5% MC. Seven screen sizes (4 5/8, 4 1/2, 4 3/8, 4 1/4, 4 1/8, 4, and 3 7/8) were used in a Carter-Day precision grader to separate the rough rice into eight thickness fractions. Mass percentages were calculated by dividing the mass of each thickness fraction by the total mass of rough rice.

RESULTS AND DISCUSSION

HRY vs. DOM Regressions

According to the method of Sun and Siebenmorgen (1993), the MRY and HRY data from each air condition duration drying treatment were linearly regressed against the corresponding DOM (Fig. 3).

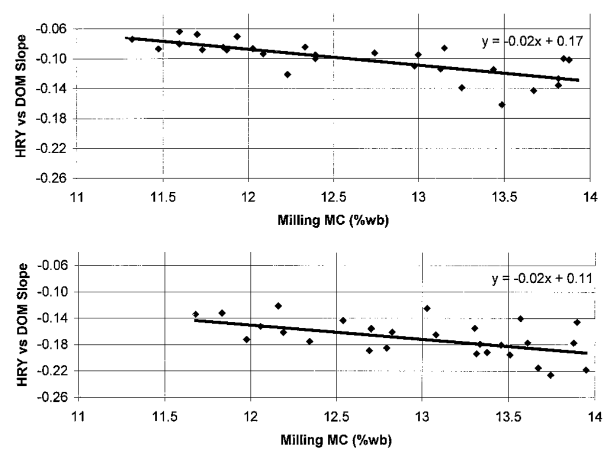

Fig. 2. Head rice yield (HRY) vs. degree of milling (DOM) slope as affected by rough rice moisture content (MC) at milling for two cultivars, Millie (top) and Lacassine (bottom).

All regressions contained eight points due to the combination of drying replicates (two) and milling durations (15, 30, 45, or 60 sec). Each of the five cultivar-harvest MC lots was dried at four air conditions for eight drying durations, creating 160 MRY and HRY vs. DOM regression data sets.

Of the 160 regressions performed, 96% were statistically significant at the 95% probability level. Data sets with insignificant regressions were removed and excluded from further analysis. The basis for further exclusion was determined by first considering the MRY or HRY vs. DOM slope (milling slope). Because it is theoretically implausible for MRY or HRY to increase as milling duration increases, regressions with positive milling slopes were excluded from further analysis with the assumption that errors had occurred in the milling or recording procedure. Other slopes were removed from the data set if $R^2 < 0.5$. Investigation of these data sets (i.e., low regression) revealed erratic MRY and HRY values, which again indicated errors in the milling, weight measurement, or recording procedure. Of the statistically significant regressions, 5% were discarded based on these criteria.

A secondary analysis of the data addressed whether or not analyzing the dependence of MRY and HRY on DOM with separate replicates resulted in statistically different slopes. The results of this secondary analysis confirmed that the slopes with separate replicates were not significantly different from those with combined replicates. Thus, replicates were combined for subsequent analysis.

Figure 3 illustrates typical regression lines of MRY and HRY versus DOM, containing the two sets of eight points resulting from the combination of drying replicates. The MRY slope represents the removal rate of bran, and possibly some endosperm, while the HRY slope also includes the loss of brokens.

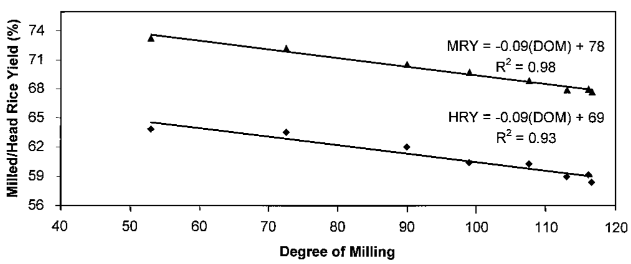

Fig. 3. A typical plot of milled rice yield (MRY) and head rice yield (HRY) vs. degree of milling (DOM), as measured with a Satake MM1-B milling meter.

TABLE I
Head Rice Yield (HRY) and Milled Rice Yield (MRY) Slope Distributions for All Drying Treatments for Each Cultivar[a]

	Slope of MRY and HRY vs. DOM[b]			
	MRY		HRY	
Cultivar	Mean	SD	Mean	SD
Lacassine	–0.14	0.023	–0.17	0.033
Millie	–0.10	0.018	–0.11	0.024
Newbonnet	–0.14	0.016	–0.14	0.019
Alan	–0.15	0.025	–0.15	0.030

[a] Slope means and standard deviations (SD).
[b] Degree of milling.

TABLE II
Coefficients for the Linear Dependence of Milling Slope on Milling Moisture Content[a] Listed by Cultivar for Milled Rice Yield (MRY) and Head Rice Yield (HRY)

	MRY		HRY	
Cultivar	α_0	α_1	α_0	α_1
Lacassine	–0.045	–0.0073	–0.044	–0.021
Millie	–0.010	–0.0073	–0.130	–0.021
Alan	–0.041	–0.0073	–0.110	–0.021
Newbonnet	–0.049	–0.0073	–0.099	–0.021

[a] Slope = $\alpha_0 + \alpha_1 \times MC_{mill}$. Milling moisture content (MC_{mill}) is presented as a percentage. $\alpha_0 = \beta_0$yield + $\beta_1$cultivar + (β_{01}yield × cultivar) $\alpha_1 = \beta_2 + \beta_{02}$yield.

Milling Slopes

Although samples were intended to equilibrate to ≈12.5% MC before milling, variation in milling MC between samples was observed. This could have been for several reasons, including variations in the control of temperature or relative humidity by the air control unit, variations in the EMC of different rice cultivars at given air conditions, and variation in EMC due to drying effects.

A relationship between milling MC and HRY slope can be seen when plotted (Fig. 2) within a cultivar. Differences in the milling slopes can be seen when the slopes are given for each cultivar (Table I). Although there was significant variance in the milling slope for any cultivar, changes in milling MC accounted for a large percentage of this variability. Analysis of variance revealed that cultivar and milling MC accounted for 44% of the variation in MRY slope and 57% of the variation in the HRY slope. The variance analysis included cultivar (four levels: Lacassine, Newbonnet, Alan, Millie), drying condition (four levels: A, B, C, D), drying duration (eight levels: 0, 15, 30, 45, 60, 120, 180, 240 min), and rough rice milling MC. The data from the two Alan harvest MC values were combined. Other factors, such as replication, drying condition, and drying duration were insignificant at the 95% confidence level. When the HRY and MRY data were combined and included as a model term, the final model was:

$$\text{Slope} = \beta_0\text{yield} + \beta_1\text{cultivar} + \beta_2 MC_{mill} + (\beta_{01}\text{yield} \times \text{cultivar}) + (\beta_{02} MC_{mill} \times \text{yield}) \quad (1)$$

which included cross terms for cultivar and yield type (MRY or HRY) as well as milling MC and yield type. This final model was rewitten as:

$$\text{Slope} = [\beta_0\text{yield} + \beta_1\text{cultivar} + (\beta_{01}\text{yield} \times \text{cultivar})] + (\beta_2 + \beta_{02}\text{yield}) \times MC_{mill} \quad (2)$$

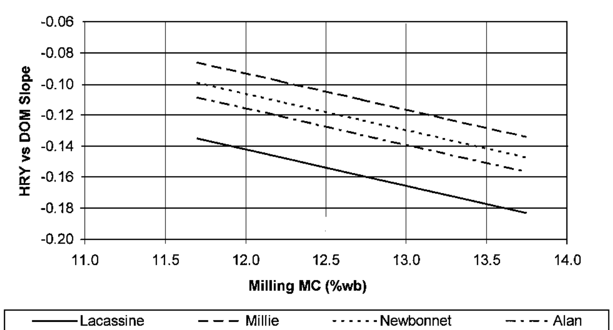

Fig. 4. Head rice yield (HRY) vs. degree of milling (DOM) slope for cultivars as affected by milling moisture content (MC). No significant differences were noted in the rate of change of the HRY vs. DOM slope with respect to milling MC when compared among cultivars.

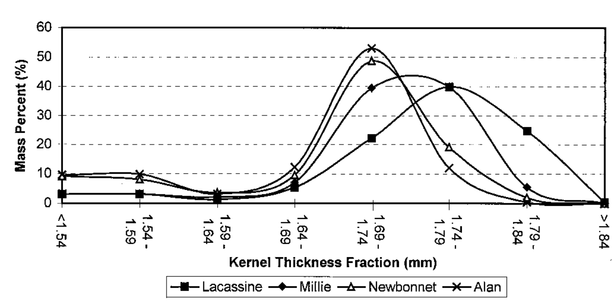

Fig. 5. Mass percentages of kernel thickness fractions for rice cultivars.

which indicates that the relationship between milling slope and milling MC depends on the cultivar and the yield being considered. The intercept of the relationship between slope and milling MC (the part inside the brackets in Eq. 2) is clearly dependent on the yield type and cultivar considered, whereas the change in milling slope with milling moisture content ($\beta_2 + \beta_{02}$yield) depends only on yield type (not cultivar). Table II summarizes the resulting statistics for the HRY and MRY of each cultivar considered.

The relationship between milling slope and milling MC suggests that as milling MC increases, the bran layers are more easily removed. According to speculation by Kohlwey (1992), this relationship between MC and ease of milling could be related to the depression of the starch gelatinization temperature as MC increases. According to Kohlwey's mechanism, bran removal occurs on areas of the kernel surface above the starch melt temperature. Nehus (1997) concluded that there is a significant dependence of starch melt temperature on milled rice MC in the range of 6–18%. Lower milled rice MC values had higher starch melt temperatures.

According to Kohlwey, the areas exceeding the starch melt temperature are removed during milling. The removed material is composed of bran and endosperm. Because starch melt temperature is lower at higher MC, it would be expected that more endosperm would be removed, along with bran, per unit of milling than at lower MC. Because more endosperm is being removed by milling at higher MC, the rate of bran plus endosperm removal as a function of bran removal (the milling slope) increases at higher MC.

The interaction between cultivar and milling MC was not a significant model term. Therefore, the rate at which the HRY versus DOM slope changed with milling MC was not influenced by varietal differences for the cultivars tested. According to the model, the HRY or MRY slope can be predicted for a given cultivar, given the MC at milling (Fig. 4). These results are limited to the long-grain cultivars because neither medium- nor short-grain cultivars were considered. The absence of a drying term suggests that the manner of drying does not affect the relationship between HRY and DOM. This is an important finding because HRY analyses are typically performed on samples without knowledge of the exact drying history of the sample.

In friction milling, interkernel abrasion is the primary mechanism for bran removal. Because kernel thickness distributions (Fig. 5) would affect interkernel abrasion, an attempt was made to explain the varietal differences in HRY slope by kernel thickness distribution. The cultivars in Table I are ordered from largest (Lacassine) to smallest (Alan) average kernel thickness. A second-order relationship between HRY slope and kernel thickness is apparent (Table I). The lack of data supporting this statement, however, cannot allow it to be further defended without additional experimentation. Further work should consider the varietal variation in groove depth as reported by Bhashyam and Srinivas (1984), who concluded that deep-grooved grains require more milling to attain a desired DOM and cause more reduction in HRY.

CONCLUSIONS

Regressions were performed on milling data obtained using the McGill no. 2 laboratory mill with standard laboratory procedures. The relationships between MRY and DOM and HRY and DOM were confirmed to be linear. Analysis of variance revealed that cultivar and milling MC accounted for 57% of the variation in the HRY versus DOM slope. Neither drying air condition nor drying duration significantly affected HRY slope. This HRY slope could be the basis of a correction method that would improve the estimation of HRY by correcting to a standard DOM for a known long-grain cultivar and milling MC. Sparse results indicate a possible relationship between average kernel thickness and HRY versus DOM slope. This relationship could explain much of the variability in the HRY versus DOM slope currently attributed to varietal differences.

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