COMPARISON OF MILLING CHARACTERISTICS
OF HYBRID AND PURELINE RICE CULTIVARS

S. B. Lanning, T. J. Siebenmorgen

ABSTRACT. *Milling characteristics vary among rice cultivars due to inherent differences in physicochemical properties. Hybrid cultivars have gained popularity due to their favorable production performance, but may exhibit different milling characteristics than pureline cultivars. A study was conducted to compare milling characteristics of two long-grain, pureline cultivars (Wells and Francis) and four long-grain, hybrid cultivars [XL723, Clearfield (CL) XL729, CL XL730, and CL XL745]. Rough rice samples of each cultivar were conditioned to 12.5% moisture content (MC) (w.b.) prior to milling, and sub-samples of four cultivars (Wells, Francis, CL XL729, and CL XL745) were conditioned to 10.5%, 11.5%, and 13.5% MC in order to evaluate the effect of MC at time of milling. Samples were milled for durations of 10, 20, 30, and 40 s. Results showed that hybrids generally reached the target surface lipid content (SLC) in a shorter duration than purelines, and that the color of hybrid head rice was generally whiter and less yellow than purelines after milling for any duration. Slopes of head rice yield (HRY) versus SLC, indicating the rate of change in HRY per unit change in SLC, varied significantly among cultivars. Milling MC had an effect on milling curves, in that rice milled at greater MC exhibited lesser SLC values and greater rates of change in HRY with respect to SLC than rice milled at lesser MC. The findings indicate a need to consider SLC in order to equitably compare milling performance and functional properties of different rice cultivars.*

Keywords. Rice quality, Milling, Hybrid rice, Moisture content.

Rice is commonly consumed as white rice, which is produced by removing the hull, germ, and bran layers from the rough rice kernel in the dehulling and milling processes, respectively. Rice lipids are mainly located in the bran and germ layers, while starch primarily comprises the starchy endosperm. Thus, removal of bran and germ during milling decreases lipid content and increases starch content of white rice (Azhakanandam et al., 2000; Park et al., 2001). The degree of milling (DOM) is often expressed as surface lipid content (SLC) and is indicative of the extent to which bran has been removed during milling, or conversely, the amount of bran remaining on kernels after the milling process (Perdon et al., 2001; Siebenmorgen et al., 2006). As such, DOM affects rice quality indices and processing characteristics, including head rice yield (HRY) (Cooper and Siebenmorgen, 2007), cooked rice texture (Saleh and Meullenet, 2007), and flour pasting parameters (Perdon et al., 2001).

Milling performance of rice may vary due to inherent physiological differences between cultivars, as well as extrinsic factors such as pre-harvest conditions and post-harvest drying and storage treatments (Thompson et al., 1990; Daniels et al., 1998; Cnossen et al., 2002; Siebenmorgen et al., 2007; Cooper et al., 2008). Pre-harvest conditions, such as harvest moisture content (HMC) and nighttime air temperature, have been shown to influence milling and functional quality of rice. Siebenmorgen et al. (2007) determined the range of optimal HMCs for long- and medium-grain rice, as defined by peak HRY, and found that lots harvested at moisture contents (MCs) below these ranges exhibited greater percentages of fissured kernels, while lots harvested above these optimal MCs exhibited greater percentages of immature kernels that are prone to breakage during milling. In a controlled-temperature study, Cooper et al. (2008) demonstrated that certain cultivars, when exposed to high nighttime air temperatures during critical reproductive stages, exhibited reduced HRY, kernel dimensions, and amylose content, as well as increased chalkiness. This research suggests that producers may influence milling yield and functionality by selecting HMCs that reduce the likelihood of fissuring in the field and planting dates that minimize the possibility of disruption of kernel development.

Drying and storage treatments are also known to affect rice physicochemical properties. Much research has been devoted to reducing drying duration while maintaining high HRY. Daniels et al. (1998) found significant interactions among drying, tempering, and storage conditions and their effects on milling quality and functionality, suggesting that changes in rice physicochemical properties are complex functions of post-harvest conditions. Andrews et al. (1992) showed that MC of rice at the time of milling played a significant role in the relationship between HRY and DOM. For a set milling duration, HRY increased as rough rice MC decreased. The increase in HRY was attributed to differences in DOM. This was supported by Thompson et al. (1990) and Bennett et al. (1993), whose findings showed greater lipid content and darker color in rice samples milled at lower MCs.

During the milling process, different properties among rice cultivars, such as kernel topography, physical dimensions, and chemical composition, have been shown to

The authors are **Sarah B. Lanning,** Research Associate, and **Terry J. Siebenmorgen, ASABE Fellow,** Professor, Food Science Department, University of Arkansas, Fayetteville, Arkansas. **Corresponding author:** Terry J. Siebenmorgen, Food Science Department, University of Arkansas, Fayetteville, AR; phone: 479-575-2841; e-mail: tsiebenm@uark.edu.

influence milling characteristics (Bhashyam and Srinivas, 1984; Chen and Siebenmorgen, 1997; Rohrer and Siebenmorgen, 2004). Bhashyam and Srinivas (1984) indicated that when a cultivar exhibiting deep kernel surface grooves is milled, bran is likely to be removed from the ridges but left remaining in the grooves. Kernels with deeper surface grooves, therefore, would require more milling pressure or longer milling durations to achieve a desired DOM. Chen and Siebenmorgen (1997) and Chen et al. (1999) reported that in a given bulk rice population, the thick kernels will be adequately milled before the thinner kernels. Milling for longer durations results in greater removal of bran, as well as endosperm, thereby reducing HRY (Reid et al., 1998). Pomeranz and Webb (1985) and Webb (1980) postulated that variation in aleurone thickness of the bran yields differences in milling performance. A study by Siebenmorgen et al. (2006) indicated that at a given milling duration, SLC and color varied among cultivars. The study specifically showed that SLC levels of two long-grain hybrids were lower than four long-grain pureline cultivars across several milling durations, suggesting that different cultivars have unique physical or chemical properties that affect their milling characteristics.

Limited information is available concerning milling behavior of hybrids compared to pureline cultivars. Extensive research has been conducted on the production performance of hybrid rice, showing that hybrids usually produce greater yields and are more resistant to major pests and diseases than conventional pureline cultivars (IRRI, 1988). For these reasons, hybrid cultivars have gained popularity in the United States in recent years. However, different milling characteristics among hybrid and pureline cultivars may result in different DOM levels, thus producing variability in HRY and inconsistent processing and end-use applications. Because of the importance of HRY in determining rice economic value, and the importance of DOM in end-use functionality, the rate at which DOM changes in relation to HRY is critical. Therefore, this study was undertaken to further evaluate and compare the milling characteristics of several hybrid and pureline rice cultivars over a range of milling MCs.

MATERIALS AND METHODS

SAMPLE PROCUREMENT AND CONDITIONING

Two long-grain, pureline cultivars (Wells and Francis) were harvested near Stuttgart, Arkansas in 2008, at HMCs of 17.2% and 14.0%, respectively (all moisture contents are expressed on a wet basis unless otherwise noted). Four long-grain, hybrid cultivars [XL723, Clearfield (CL) XL729, CL XL730, and CL XL745] were harvested near Jonesboro, Arkansas in 2008, at HMCs of 13.4%, 13.9%, 13.7%, and 13.2%, respectively. Samples of each cultivar lot were cleaned (Carter-Day Dockage Tester, Carter-Day Co., Minneapolis, Minn.) and dried in a chamber maintained at 21°C and 62% relative humidity (RH) by a temperature and RH controller (AA5582, Parameter Generation & Control, Inc., Black Mountain, N.C.). The rough rice equilibrium MC corresponding to these conditions was approximately 12.5% (*ASABE Standards*, 2007).

To evaluate the effect of rough rice MC on the milling quality of rice cultivars, sub-samples of Wells, Francis, CL

XL729, and CL XL745 were conditioned to MCs of approximately 10.5%, 11.5%, and 13.5%, using the afore-mentioned chamber, maintained at 21°C and RHs of 44.5%, 53.5%, and 70.0%, respectively. Durations required to achieve the desired MCs ranged from 48 to 168 h, depending on the initial MC of the sample. Rough rice MCs were measured by drying 15 samples in triplicate at 130°C for 24 h in a convection oven (1370FM, Sheldon Manufacturing, Inc., Cornelius, Oreg.) according to the method of Jindal and Siebenmorgen (1987).

MILLING QUALITY

Prior to milling, rice samples were removed from storage and equilibrated to room temperature in plastic bags for at least 12 h. For each milling test, a 150-g rough rice sample was first dehulled in a laboratory sheller (THU, Satake, Tokyo, Japan) with a clearance of 0.048 cm (0.019 in.) between the rollers. The resultant brown rice sample was milled for 10, 20, 30, or 40 s using a laboratory mill (McGill No. 2, RAPSCO, Brookshire, Tex.) to achieve varying DOM levels. The mill had a 1.5-kg weight on the lever arm, situated 15 cm from the milling chamber. Head rice, comprised of milled kernels that are at least three-quarters of their original length (USDA, 2005), was separated from brokens using a sizing device (Seedburo Equipment Co., Chicago, Ill.). Head rice yield was expressed as the mass percentage of the 150 g of rough rice that remained as head rice. Three replications of the milling procedure were performed for each milling duration, resulting in 12 milling tests per lot. Seventy-two milling trials of the 12.5%-MC lots (six rice lots × four milling durations × three replications) were performed. Conditioned sub-samples of Wells, Francis, CL XL729, and CL XL745 cultivars were milled at rough rice MCs of 10.5%, 11.5%, and 13.5%, resulting in an additional 144 milling trials (four rice lots × three rough rice MCs × four milling durations × three replications).

TOTAL LIPID CONTENT

Total lipid content (TLC) of brown rice samples from the 12.5%-MC rough rice lots was measured. It is to be noted that with the sheller roller clearance used, approximately 92% of the rough rice in each sample was dehulled. The remaining 8% of kernels, with hulls intact, were manually removed from the brown rice before measuring TLC. A cyclone sample mill (3010-30, Udy, Fort Collins, Colo.) fitted with a 100-mesh (0.5-cm) sieve was used for grinding brown rice samples. Brown rice TLC was determined in duplicate using a lipid extraction system (Avanti 2055, Foss North America, Eden Prairie, Minn.) according to AACC method 30-20 (AACC International, 2000), with modifications to the petroleum ether washing duration, as described by Matsler and Siebenmorgen (2005). In brief, 5 g of brown rice flour were weighed into cellulose thimbles (Foss North America, Eden Prairie, Minn.); the thimbles and brown rice flour were pre-dried for 1 h in a 100°C oven. Subsequently, 70 mL of petroleum ether (boiling point 35-60°C; VWR, Suwanee, Ga.) were added to each extraction cup. Samples were boiled in solvent for 20 min over a 135°C hot plate then rinsed with petroleum ether condensate for 30 min. A 5-min solvent recovery step followed. After the extraction cycle, the extraction cups were removed from the lipid extraction unit and placed into an oven maintained at 100°C for 30 min to

evaporate the solvent. The extraction cups were placed in a dessicator at room temperature for approximately 30 min to cool before weighing. The difference between the mass of the cups containing the extracted lipid and the original empty cup mass was calculated to obtain the mass of the extracted lipid. Total lipid content was expressed as the mass percentage of extracted lipid to the original brown rice.

SURFACE LIPID CONTENT

Surface lipid content (SLC) of each head rice sample was measured using a diode array analyzer (DA7200, Perten Instruments, Huddinge, Sweden). In brief, a 60-g sample of head rice was placed into the analyzer's 75-mm diameter sample container, which was rotated during the diode array analysis. Absorbance readings were collected over a near-infrared wavelength range of 950 to 1650 nanometers (nm), at 5-nm increments. Surface lipid content was predicted using the calibration of Saleh et al. (2008). Three scans were collected from each sample and average SLC values were calculated.

CALCULATION OF PERCENT REDUCTION IN SLC

In order to account for variation in initial lipid content among the cultivars, the percent reduction in SLC was calculated after each milling duration. Percent reduction in head rice SLC was calculated as the difference between the TLC of a brown rice sample and the resulting SLC after a given milling duration, divided by the TLC. It should be noted that the TLC of each brown rice sample was used to represent the initial lipid content, because previous research has shown that the SLC determination procedure, when applied to brown rice, produces erroneously low values (Siebenmorgen et al., 2006). This is thought to be due to the waxy seed coat, which surrounds the caryopsis (Champagne et al., 2004), inhibiting penetration of petroleum ether during lipid extraction. Grinding brown rice, as described above, allows for penetration of the solvent, so as to provide an accurate measure of the lipids in a brown rice sample. The majority of lipids are located in the bran layers and germ, which are removed, to varying extent, during the milling process.

COLOR

The L^* (black to white) and b^* (blue to yellow) color profiles of head rice were measured using a color meter (Colorflex EZ, Hunterlab, Reston, Va.). Approximately 35 g of each sample were placed in a 5-cm diameter glass sample cup with an opaque cover. After the first color measurement was taken, the sample cup was rotated 90° and a second measurement was performed. An average of the two readings was recorded for each sample.

DATA ANALYSIS

Head rice yield versus SLC plots were developed using statistical software (JMP release 8.0, SAS institute, Cary, N.C.). Analysis of variance (ANOVA) was performed using least significant differences (LSD), at a 5% level of probability, to determine the significance of the differences observed between HRY versus SLC slopes.

RESULTS AND DISSCUSION
MILLING OF HYBRID AND PURELINE RICE

Since it is known that HRY is directly affected by DOM, figure 1 was constructed to illustrate HRY versus SLC relationships (sometimes referred to as "millability" curves in the rice processing industry) for cultivars milled at a rough rice MC of approximately 12.5% for 10, 20, 30, and 40 s. Head rice yield was linearly and directly correlated with SLC, confirming trends reported by Reid et al. (1998) and Cooper and Siebenmorgen (2007). Slopes of the regression lines, indicating the rate of change in HRY per unit change in SLC for hybrid and pureline cultivars, are presented in table 1. At an approximate milling MC of 12.5%, hybrid cultivar CL XL745 had the greatest rate of change in HRY, followed by XL723 and Wells, with HRY changes of 14.4, 12.3, and 10.7 percentage points (pp) for every 1.0-pp change in SLC, respectively (table 1). The average slope across all cultivars at a milling MC of 12.5% was 10.7, which is slightly lower than that observed by Pereira et al. (2008), who found that long-grain cultivars averaged a change of 11.3 pp in HRY for every 1.0-pp change in SLC. These findings suggest that
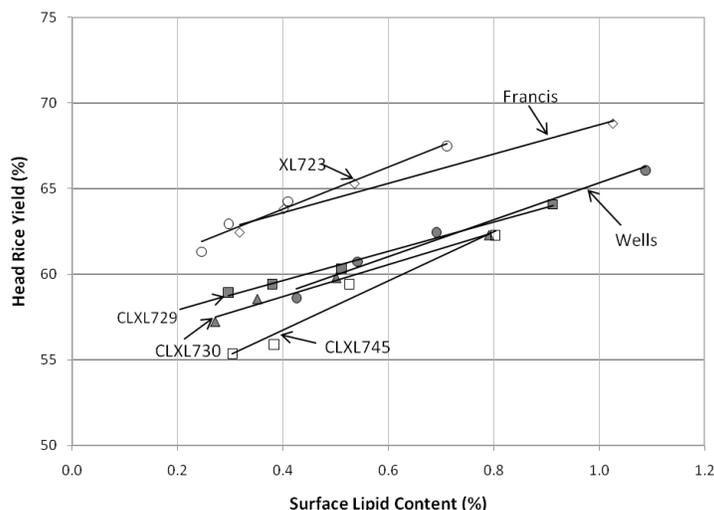

Figure 1. Head rice yield vs. head rice surface lipid content of the indicated cultivars milled at a rough rice moisture content of approximately 12.5% (w.b.) for 10, 20, 30, and 40 s using a laboratory mill. Each data point represents the average of three milling replications.

Table 1. Slopes, intercepts and coefficients of determination (R^2) of linear regression lines relating head rice yield to head rice surface lipid content of pureline (Wells and Francis) and hybrid (XL723, CL XL729, CL XL730 and CL XL745) rice cultivars milled at target rough rice moisture contents of 10.5%, 11.5%, 12.5%, and 13.5% for 10, 20, 30, and 40 s in a laboratory mill.[a]

Cultivars	Harvest (%)	Rough Rice Moisture Content (%) Milling (%)		Head Rice Yield vs. Head Rice Surface Lipid Content		Brown Rice Total Lipid Content (%)[c]
		Target	Actual	Slope[b]	R^2	
Purelines						
Wells	17.2	10.5	10.7	8.3b,B	0.97	
		11.5	11.5	8.3b,A	0.88	
		12.5	12.6	10.7a,BC	0.93	2.70a
		13.5	13.4	12.7a,B	0.88	
Francis	14.0	10.5	10.6	8.1b,B	0.96	
		11.5	11.6	7.3b,A	0.85	
		12.5	12.5	8.5b,D	0.94	2.68ab
		13.5	13.4	17.1a,A	0.93	
Hybrids						
XL723	13.4	12.5	12.5	12.3B	0.96	2.45d
CL XL729	13.9	10.5	10.6	7.0b,B	0.96	
		11.5	11.4	6.9b,A	0.93	
		12.5	12.4	8.6b,D	0.97	2.51cd
		13.5	13.4	13.0a,B	0.93	
CL XL730	13.7	12.5	12.6	9.5CD	0.89	2.45d
CL XL745	13.2	10.5	10.8	10.2c,A	0.93	
		11.5	11.3	7.2d,A	0.93	
		12.5	12.7	14.4b,A	0.94	2.55cd
		13.5	13.5	19.0a,A	0.93	

[a] Brown rice total lipid content of rough rice conditioned to 12.5% moisture content is also presented.
[b] Lower-case letters represent significant differences in slope among moisture content lots within a cultivar; upper-case letters represent significant differences in slope between cultivars at a given target moisture content.
[c] Brown rice total lipid contents of pureline and hybrid cultivars with different letters are significantly different according to an LSD test at a 0.05 level of significance.

different milling characteristics among cultivars can significantly impact HRY.

Many studies attribute differences in milling performance of hybrid and pureline cultivars to variation in bran layer thickness or bran/embryo chemical composition. Rice lipid is predominantly located in the aleurone, subaleurone, and germ of rice bran (Champagne et. al, 2004). Pomeranz and Webb (1985) and Webb (1980) postulated that high TLC is indicative of thick bran layers, while low TLC is associated with thin bran layers. Rohrer and Siebenmorgen (2004) suggested that lipid, as a constituent of the bran, may differ in content among cultivars, as well as kernel thickness fractions. These hypotheses are substantiated by significant differences observed in TLC among cultivars in the current study (table 1) and it is reasonable to assume that given a lesser initial lipid content, SLC after milling would be correspondingly less.

However, the current study finds that milling characteristics differ between hybrid and pureline cultivars, even when TLC is taken into consideration. Figure 2 illustrates the percent reduction in SLC observed at 10-s intervals over a milling duration of 40 s for the four hybrid and two pureline cultivars milled at rough rice MCs of approximately 12.5%. Percent reduction in SLC was used to account for the variation in TLC among cultivars prior to milling. Results showed that hybrids generally exhibited greater reductions in SLC than both purelines when milled for short durations (<20 s). Pureline cultivar Francis reached SLC reduction levels similar to the hybrids between 15 and 20 s of milling, but pureline Wells consistently exhibited the least reduction in SLC across all milling durations, while hybrid XL723 produced the greatest reduction. These findings suggest that DOM is not simply a function of initial lipid content, but also a function of the rate at which lipids are removed from the endosperm during the milling process, which differs among cultivars.

These results have dramatic implications for estimating milling quality using laboratory mills, as the DOM reached at set milling durations varied greatly between hybrid and pureline cultivars. Figure 3 shows the actual SLC versus milling duration curves of hybrid and pureline cultivars milled at rough rice MCs of approximately 12.5% for 10, 20, 30, and 40 s. Hybrids XL723, CL XL730, CL XL745, and CL XL729 milled for 30 s resulted in SLCs of 0.30%, 0.35%, 0.38%, and 0.38%, while pureline Wells, milled for the same duration, resulted in a greater SLC of 0.54%. Alternately, achieving a target SLC required a shorter milling duration for hybrids than purelines. A target SLC of 0.60% was reached in hybrids XL723, CL XL730, CL XL745, and CL XL729 after 13, 16, 17, and 18 s, while Francis and Wells purelines required 19 and 25 s, respectively. These findings accentuate the need to control milling duration with respect to attaining a desired SLC in order to equitably compare HRYs of different cultivars. Assuming that the observed milling behavior in the McGill #2 mill extends to commercial mills, the findings have implications to mill personnel in terms of greater throughput of hybrids over some pureline cultivars.
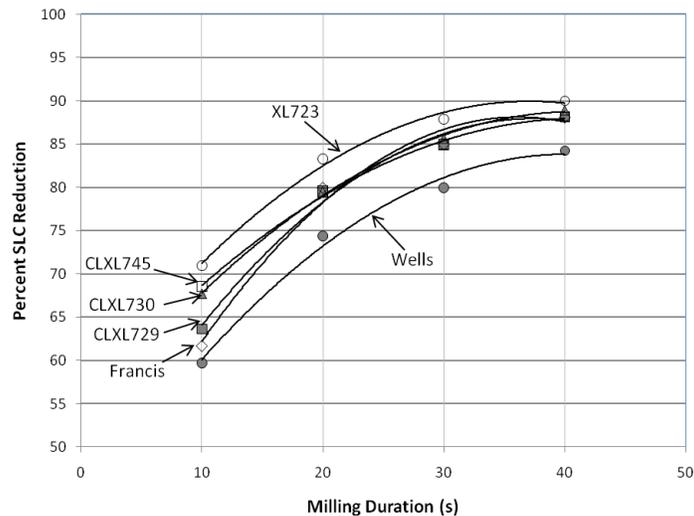
Figure 2. Percent reduction in head rice surface lipid content (SLC) of the indicated cultivars after milling at a rough rice moisture content of approximately 12.5% (w.b.) for 10, 20, 30, and 40 s in a laboratory mill. Each data point represents the average reduction in SLC from the corresponding brown rice total lipid content of each cultivar, as measured from three replications of each milling duration.

HYBRID AND PURELINE RICE COLOR

Color parameters L^* and b^* of head rice lots that were milled at rough rice MC of 12.5% for 10, 20, 30, and 40 s are presented in figure 4. As expected, milling had a significant effect on head rice color. Head rice became significantly (α = 0.05) whiter (L^* value) and less yellow (b^* value) as milling duration increased. These results paralleled those of Lamberts et al. (2007), in that the levels of whiteness increased and the red and yellow pigments decreased from the surface of the brown rice to the starchy endosperm.

Generally, the color of hybrid head rice was whiter and less yellow than pureline head rice when milled for any duration (fig. 4), indicating a greater degree of bran removal or inherently whiter endosperm. These results correspond to the SLC trends (fig. 3), again suggesting that hybrids may be over-milled when processed under milling conditions developed around pureline cultivars. L^* and b^* values were significantly correlated with SLC, showing correlation coefficients of -0.98 and 0.97, respectively. A similar

observation was reported by Graves et al. (2009), who showed strong correlations between SLC and head rice color parameters. It should be noted that for all cultivars, both L^* and b^* color values began to plateau after 20 to 30 s of milling (fig. 4). This suggests that over-milling may compromise yield with diminishing gains in color quality.

ROUGH RICE MC EFFECT ON MILLING QUALITY

Rough rice MC at the time of milling had a significant effect on milling performance. Figure 5 shows plots of head rice SLC for Wells, Francis, CL XL729, and CL XL745 milled at rough rice MCs of 10.5%, 11.5%, 12.5%, and 13.5% for 10, 20, 30, and 40 s. Even when milled for a short duration (10 s), rice at greater MC exhibited significantly lower SLC levels than did rice at lesser MC. For example, across all cultivars, samples milled at 10.5% MC for 10 s produced SLCs ranging from 1.01% to 1.15%, while samples milled at 13.5% MC for the same duration had SLC values ranging from 0.67% to 0.75%.
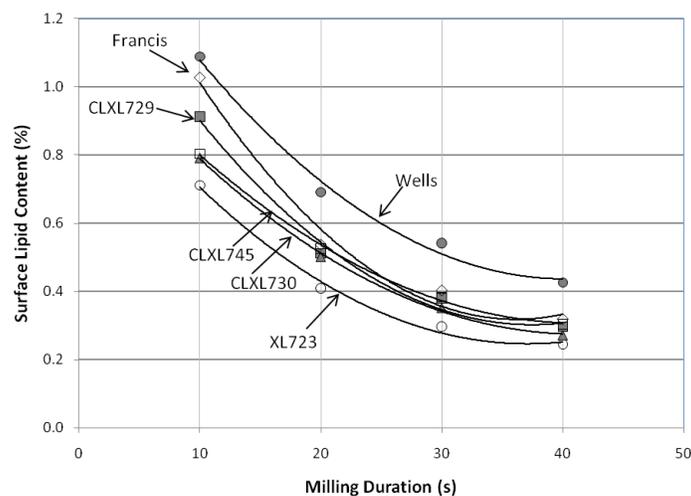

Figure 3. Head rice surface lipid contents of Wells, Francis, XL723, CL XL729, CL XL730, and CL XL745 cultivars after milling at rough rice moisture contents of approximately 12.5% (w.b.) for 10, 20, 30, and 40 s using a laboratory mill. Each data point represents the average surface lipid content measured from three replications of each milling duration.
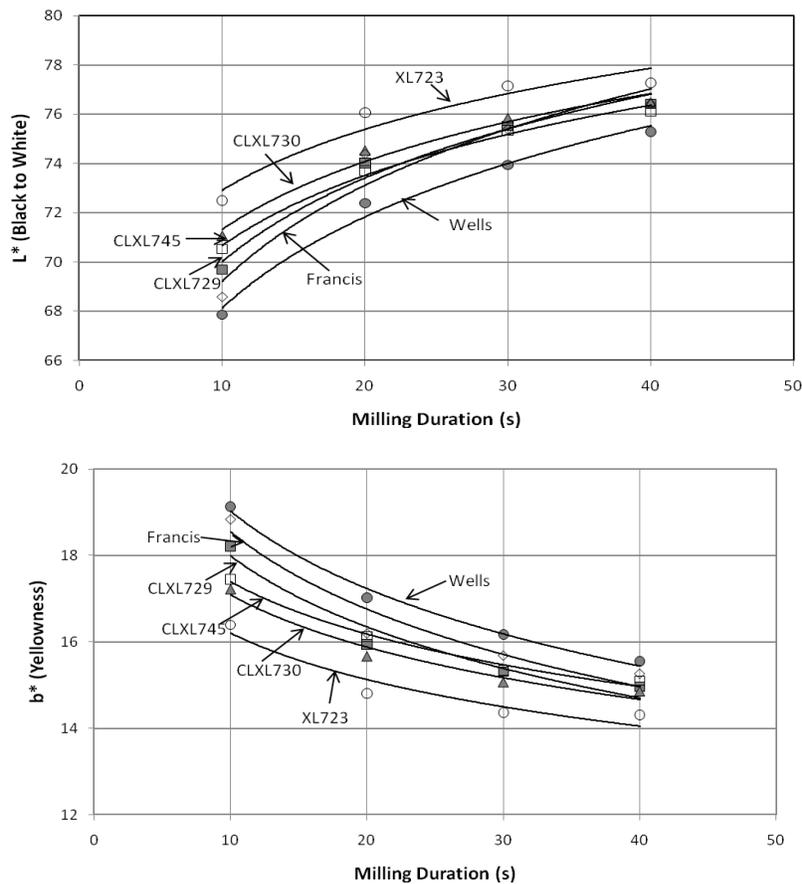
Figure 4. Head rice color (*L** and *b** values) of Wells, Francis, XL723, CL XL729, CL XL730, and CL XL745 cultivars milled at a rough rice moisture contents of approximately 12.5% (w.b.) for 10, 20, 30, and 40 s using a laboratory mill. Greater *L** values represent greater whiteness, while greater *b** values represent greater yellowness. Each data point represents the average color value (*L** or *b**) from three replications of each milling duration.

For hybrids, differences in SLC between high and low MCs became less significant as milling duration increased. Figure 5 shows a diminished effect of MC on the SLCs of hybrids after 20 s of milling, while purelines showed a MC effect even after 40 s. These results suggest that differences in physicochemical properties between hybrid and pureline cultivars, such as the TLC of brown rice, play a significant role in bran removal.

Figure 6 illustrates HRY versus SLC curves for CL XL729, CL XL745, Wells, and Francis cultivars milled at 10.5%, 11.5%, 12.5%, and 13.5% rough rice MCs for durations of 10, 20, 30, and 40 s. Samples milled at greater rough rice MCs had greater slopes, i.e. greater rates of change in HRY with respect to change in SLC (table 1). For example, the HRY of Wells cultivar milled at 10.5% MC changed 8.3 pp for every 1.0-pp change in SLC, whereas the HRY of the same rice milled at 12.5% and 13.5% MC changed 10.7 and 12.7 pp for every 1.0-pp change in SLC, respectively. These trends suggest that bran is more easily removed as MC increases. Reid et al. (1998) also found that milling MC, as well as cultivar, significantly influenced the rate at which HRY changed with DOM.

The trends in HRY versus SLC regression slopes of Wells, Francis, CL XL729, and CL XL745 cultivars milled at various MCs for 10, 20, 30, and 40 s are illustrated in figure 7. Increases in slopes were most significant at or above 12.5% MC across all cultivars. Similar trends relating milling MC to HRY have been reported. Banaszek et al. (1989) showed

an increase in HRY with decrease in MC of rough rice when milling for a constant duration using a McGill No. 2 laboratory mill. Thompson et al. (1990) reported an increase in HRY with a decrease in milling MC, which was attributed to variation in DOM. Greater lipid content and darker rice, indicators of under-milling, were also reported when milling at low MC. Bennett et al. (1993) showed a reduction in surface lipid removal with a decrease in rough rice MC at milling. Afzalinia et al. (2004) found 12% to 14% MC to be optimal for milling, with regard to minimizing breakage.

The increasing rate of bran removal with increasing MC suggests that rice kernel physical properties impacting bran removal change with MC. Kohlwey (1992) speculated that bran removal is facilitated by a micro-scale gelatinization of starch, which occurs at the surface of the endosperm due to increased temperature resulting from friction in the milling process. Greater MC results in decreased starch gelatinization temperature, which may allow greater ease of bran removal. Kohlwey's speculation also suggests that a greater milling MC could result in more endosperm entering the bran stream, which may explain the observations of figure 6, showing that even at an equivalent SLC, HRYs tended to be lower as MC increased. A future study measuring starch content of the bran stream and the amount of broken kernels generated during milling would help to confirm this speculation.
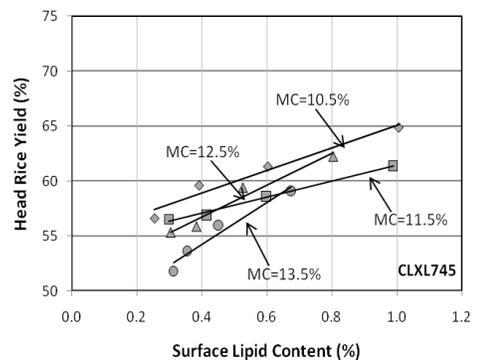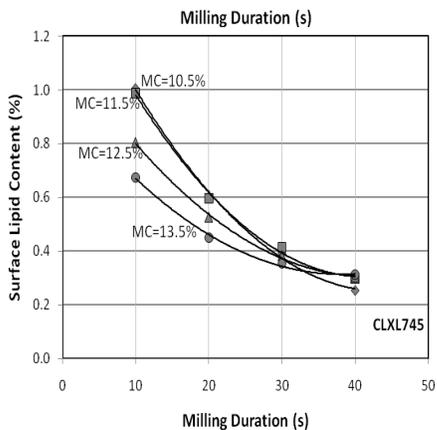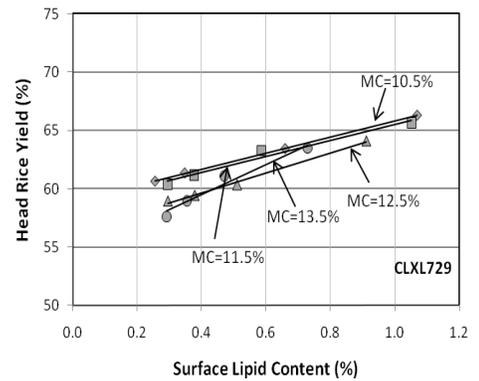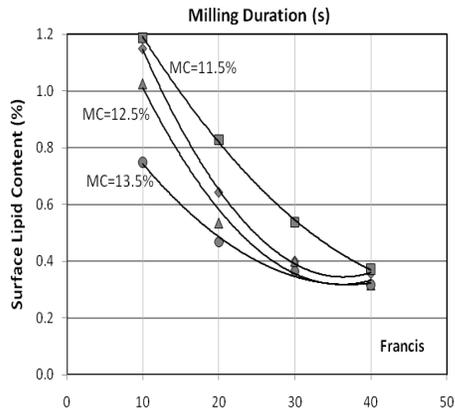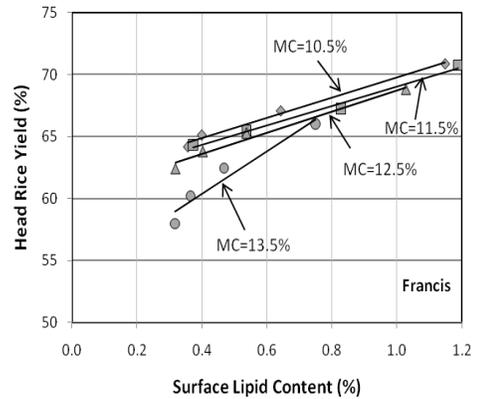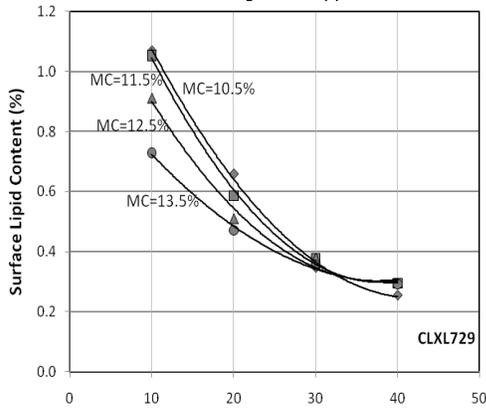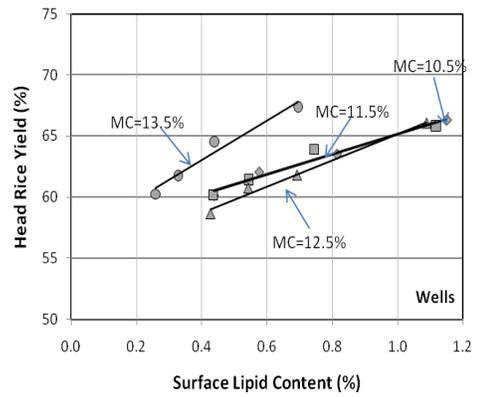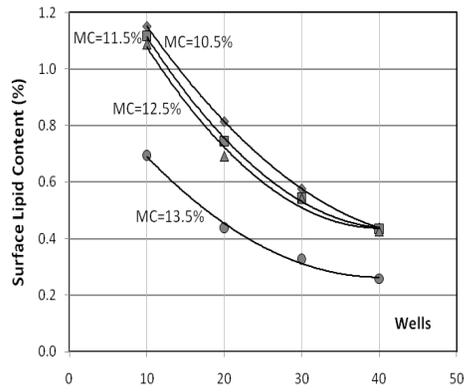
Figure 5. Head rice surface lipid content of Wells, Francis, CL XL729, and CL XL745 cultivars after milling at rough rice moisture contents of approximately 10.5%, 11.5%, 12.5%, and 13.5% (w.b.) for 10, 20, 30, and 40 s using a laboratory mill. Each data point represents an average surface lipid content measured from three replications of each milling duration.

Figure 6. Head rice yield vs. head rice surface lipid content for Wells, Francis, CL XL729, and CL XL745 cultivars milled at rough rice moisture contents of approximately 10.5%, 11.5%, 12.5%, and 13.5% (w.b.) for 10, 20, 30, and 40 s using a laboratory mill. Each data point represents the average of three milling replications.
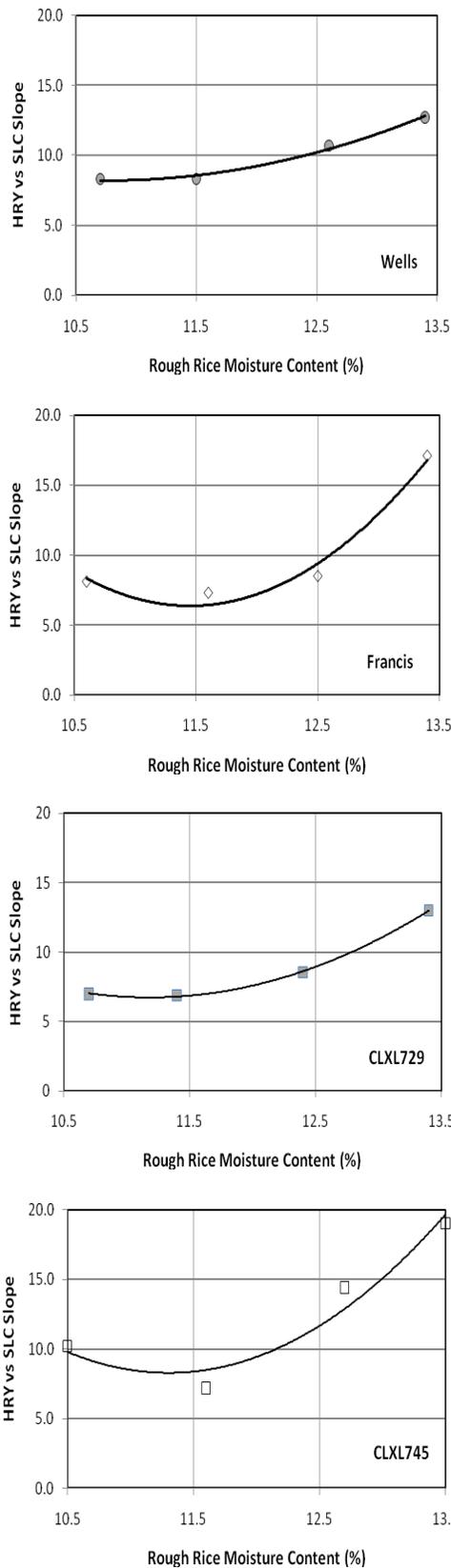
Figure 7. Head rice yield (HRY) vs. surface lipid content (SLC) regression line slopes of Wells, Francis, CL XL729, and CL XL745 cultivars milled at rough rice moisture contents of approximately 10.5%, 11.5%, 12.5%, and 13.5% (w.b.) for 10, 20, 30, and 40 s using a laboratory mill. Each data point represents the average slope calculated from each of three milling replications.

CONCLUSIONS

Results of this study showed differences in the milling characteristics of hybrid and pureline cultivars, in that hybrids required shorter milling durations than purelines to achieve comparable DOM. Hybrids generally exhibited greater DOM, as evidenced by lower SLC and greater L^* values, for any given milling duration. These results may be attributed in part to lesser lipid content in the bran/germ layers of hybrids, as shown by differences in brown rice total lipid content, as well as differences in the rate at which lipids are removed during the milling process. As expected, HRY was linearly and directly correlated with head rice SLC for hybrid and pureline cultivars.

The MC of rough rice at the time of milling influenced milling performance. Greater milling MCs generally resulted in a greater rate of change in HRY with respect to SLC, possibly due to a greater amount of endosperm entering the bran stream. Across all MCs, hybrid cultivar CL XL745 exhibited the greatest rate of change in HRY per unit SLC.

These findings emphasize the importance of understanding how milling characteristics differ among rice cultivars, as well as with milling MC. Due to these differences, SLC should be considered in order to better compare HRY and subsequent measurements of functional properties that are affected by DOM, particularly between hybrid and pureline cultivars.

ACKNOWLEDGEMENTS

REFERENCES

AACC International. 2000. Approved Methods of Analysis, 10th Ed. Method 30-20. Crude Fat in Grain and Stock Feeds. St. Paul, Minn. AACC International.

Afzalinia, S., M. Shaker, and E. Zare. 2004. Comparison of different rice milling methods. *Canadian Biosystems Eng*. 46(3): 63-66.

Andrews, S. B., T .J. Siebenmorgen, and A. Mauroumoustakos. 1992. Evaluation of the McGill No. 2 Rice Miller. *Cereal Chem*. 69(1):35-43.

ASABE Standards. 2007. Moisture relationship of plant based agricultural products. St. Joseph, Mich.: ASABE.

Azhakanandam, K., J. B. Power, K. C. Lowe, E. C. Cocking, T. Tongdang, H. F. J. Bligh, S. E. Harding, and M. R. Davey. 2000. Qualitative assessment of aromatic *Indica* rice *Oryza sativa* L. proteins, lipids and starch in grain from somatic embryo- and seed-derived plants. *J. Plant Physiol*. 156(5-6): 783-789.

Banaszek, M., T. Siebenmorgen, and C. Sharp. 1989. Effects of moisture content at milling on head rice yield and degree of milling. *AR Farm Res*. 38(2): 15.

Bennett, K. E., T. J. Siebenmorgen, and A. Mauroumoustakos. 1993. Effect of McGill No. 2 miller settings on surface fat concentration of head rice. *Cereal Chem*. 70(6): 734-739.

Bhashyam, M. K., and T. Srinivas. 1984. Varietal difference in the topography of rice grain and its influence on milling quality. *J. Food Sci*. 49(2): 393-401.

Champagne, E. T., D. F. Wood, B. O. Juliano, and D. B. Bechtel. 2004. The rice grain and its gross composition. In *Rice: Chemistry and Technology*, 77-107. 3rd ed. E. T. Champagne, ed. St. Paul, Minn.: American Assoc. Cereal Chem.

Chen, H., and T. J. Siebenmorgen. 1997. Effect of rice kernel thickness on degree of milling and associated optical measurements. *Cereal Chem.* 74(6): 821-825.

Chen, H., T. J. Siebenmorgen, and L. Du. 1999. Quality characteristics of medium-grain rice milled in a three-break commercial milling system. *Cereal Chem.* 76(4): 473-475.

Cnossen, A. G., T. J. Siebenmorgen, and W. Yang. 2002. The glass transition temperature concept in rice drying and tempering: effect on drying rate. *Trans. ASAE* 45(3): 579-766.

Cooper, N. T. W., and T. J. Siebenmorgen. 2007. Correcting head rice yield for surface lipid content (degree of milling) variation. *Cereal Chem.* 84(1): 88-91.

Cooper, N. T. W., T. J. Siebenmorgen, and P. A. Counce. 2008. Effects of nighttime temperature during kernel development on rice physicochemical properties. *Cereal Chem.* 85(3): 276-282.

Daniels, M. J., B. P. Marks, T. J. Siebenmorgen, R. W. McNew, and J. F. Meullenet. 1998. Effects of long-grain rough rice storage history on end-use quality. *J. Food Sci.* 63(5): 832-835.

Graves, A. M., T. J. Siebenmorgen, and M. I. Saleh. 2009. A comparative study between the McGill No. 2 laboratory mill and commercial milling systems. *Cereal Chem.* 86(4): 470-476.

IRRI. 1988. *Hybrid Rice: Proc. of the Intl. Symposium of Hybrid Rice.* Los Baños, Philippines: IRRI.

Jindal, V. K. and T. J. Siebenmorgen. 1987. Effects of oven drying temperature and drying time on rough rice moisture content determination. *Trans. ASAE* 30(4): 1185-1192.

Kohlwey, D. E. 1992. The quest for the whole grain in rice milling. *Cereal Foods World* 37(8): 633-639.

Lamberts, L., E. De Bie, G. E. Vandeputte, W. S. Veraverbeke, V. Derycke, W. De Man, and J. A. Delcour. 2007. Effect of milling on colour and nutritional properties of rice. *Food Chem.* 100(4): 1496-1503.

Matsler, A.L. and Siebenmorgen, T.J. 2005. Evaluation of operating conditions for surface lipid extraction from rice using a Soxtec system. *Cereal Chem.*, 82(3): 282-286.

Park, J. K., S. S. Kim, and K. O. Kim. 2001. Effect of milling ratio on sensory properties of cooked rice and on physicochemical properties of milled and cooked rice. *Cereal Chem.* 78(2): 151-156.

Perdon, A. A., T. J. Siebenmorgen, A. Mauromoustakos, V. K. Griffin, and E. R. Johnson. 2001. Degree of milling effects on rice pasting properties. *Cereal Chem.* 78(2): 205-209.

Pereira, T., N. Cooper, and T. Siebenmorgen. 2008. Effects of storage temperature and duration on the milling properties of rice. *Discovery* 9: 64-74.

Pomeranz, Y., and B. D. Webb. 1985. Rice hardness and functional properties. *Cereal Foods World* 30(11): 784-788.

Reid, J. D., T. J. Siebenmorgen, and A. Mauromoustakos. 1998. Factors affecting the slope of head rice yield versus degree of milling. *Cereal Chem.* 75(5): 738-41.

Rohrer, C. A., and T. J. Siebenmorgen. 2004. Nutraceutical concentrations within the bran of various rice kernel thickness fractions. *Biosystems Eng.* 88(4): 453-60.

Saleh, M. I., and J. F. Meullenet. 2007. Effect of moisture content at harvest and degree of milling (based on surface lipid content) on the texture properties of cooked long-grain rice. *Cereal Chem.* 84(2): 119-124.

Saleh, M. I., J. F. Meullenet, and T. J. Siebenmorgen. 2008. Development and validation of prediction models for rice surface lipid content and color parameters using near-infrared spectroscopy: A basis for predicting rice degree of milling. *Cereal Chem.* 85(6): 787-791.

Siebenmorgen, T. J., R. C. Bautista, and P. A. Counce. 2007. Optimal harvest moisture contents for maximizing milling quality of long- and medium-grain rice cultivars. *Trans. ASAE* 23(4): 517-527.

Siebenmorgen, T. J., A. L. Matsler, and C. F. Earp. 2006. Milling characteristics of rice cultivars and hybrids. *Cereal Chem.* 83(2): 169-172.

Thompson, J. F., J. Knutson, and B. Jenkins. 1990. Analysis of variability in rice milling appraisals. *Trans. ASAE* 6(2): 194-198.

USDA. 2005. United States Standards for Rice, revised. Washington, D.C.: Federal Grain Inspection Service.

Webb, B. D. 1980. Rice quality and grades. In *Rice: Production and Utilization*, 543-565. B. S. Luh, ed. Westport, Conn.: AVI Publishing.