Effect of Moisture Content at Harvest and Degree of Milling (Based on Surface Lipid Content) on the Texture Properties of Cooked Long-Grain Rice

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ABSTRACT

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The effects of the degree of milling (based on surface lipids content [SLC]) on cooked rice physicochemical properties were investigated. Head rice yield (HRY), protein, and SLC decreased with increasing milling, while the percent of bran removed and whiteness increased. Results showed that SLC significantly ($P < 0.05$) affected milled as well as cooked rice properties across cultivar, moisture content (MC) at harvest, and location (Stuttgart, AR, and Essex, MO). Cooked rice firmness ranged from 90.12 to 111.26 N after milling to various degrees (SLC). The decrease in cooked rice firmness with increasing milling was attributed to the lowering of total proteins and SLC. Cooked rice water uptake increased with increasing degree of milling. Water uptake by the kernel during cooking dictated the cooked rice firmness. The increase in cooked rice stickiness with increasing degree of milling was attributed to an increase in starch leaching during cooking because of the greater starch granule swelling associated with a greater water uptake.

Rice is usually used as milled whole rice after removing the outer hull and the bran layers of the rough rice. The measure of how much bran is removed during the milling process is known as the degree of milling (DOM) (Perdon et al 2001). However, the amount of bran removed varies depending on dehulling and milling processes. Therefore, variations in DOM result in changes in the rice kernel gross composition. For example, Juliano (1985) indicated that >98% of the SLC and >50% of proteins are usually removed by milling. The removal of the outer layers of rough rice, due to milling, was reported to cause disproportionate losses of lipids, proteins, reducing sugars, and minor components that increase the total amount of starch in milled rice (Singh et al 1998; Azhakanandam et al 2000; Park et al 2001). In addition to milling conditions, the chemical composition of the rice grain also depends on the cultivar, variability in the environment (McClung 2004; Copeland and Dang 2005; Counce et al 2005), cultural practices, and soil type (Park et al 2001).

Starch, proteins, lipids, and their interaction have long been reported to influence rice functional properties (Eliasson and Krog 1985; Chrastil 1993; Vandeputte et al 2003). For instance, Wang et al (2003) reported that although pasting properties of rice flour were affected by the drying regimes of rough rice, there were no indications of changes in starch molecular size distribution, pointing out the important role of other grain components (i.e., proteins and lipids) in determining the functional properties of rice kernels.

Rice MC at harvest, as an indicator of rice kernel development, is another important factor that affects rice quality (Siebenmorgen et al 2004). For instance, draining and harvesting date, which influence rice MC at harvest, have been reported to affect rice metabolic processes and starch and protein composition as well as structure (Champagne et al 2005). Although starch and protein synthesis is thought to be complete when rice moisture content reaches 27–29%, a slight decrease in rice proteins and lipids and an increase in amylose content have been reported (Siebenmorgen et al 2004; Champagne et al 2005). This could be because a bulk of rice at 27–29% still contains a significant proportion of immature kernels. Because small variations in rice chemical composition may result in changes in rice physicochemical properties (Chrastil 1990), variations in rice harvest MC are expected to lead to variation in functional properties such as cooked rice texture.

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Various methods have been employed to mill rice samples to various DOM levels. Perdon et al (2001) used milling durations of 15, 30, 45, and 60 sec in a McGill No. 2 laboratory mill to produce samples with varying DOM, while other authors (Kim et al 2001) used the percentage of bran removed after milling as an indication of DOM. However, milling for set durations can yield rice of varying DOM because of factors such as rice cultivar, rice MC, rice temperature, or mill settings (Andrews et al 1992; Bennett et al 1993; Archer and Siebenmorgen 1995). Practices for target DOM seem to vary quite extensively throughout the world, probably because of varying consumer preferences in specific markets. A higher DOM tends to make rice whiter, which is often associated with higher quality rice but may also negatively impact the sensory quality of cooked rice (Kwon and Jeon 1991). Therefore, the optimum DOM is usually determined based on the eating preference for cooked rice by specific consumer groups.

A thorough investigation of the effect of rice milling on texture properties is important to understand the relationship between DOM, rice cooking, and cooked rice texture properties. Therefore, the objective of this study was to investigate the effect of DOM (based on SLC) of rice harvested at various MC on the instrumental texture properties of cooked rice.

MATERIALS AND METHODS

Rice Samples and Rice Fractionation

Two long-grain rice cultivars (Francis and Wells) (≈200 lb of hand-harvested samples from each cultivar before size fractionation) harvested in the fall of 2004 from two different locations (Stuttgart, AR, and Essex MO) at low MC (12.8–16.3%) and high MC (21.0–22.0%) were used in this study. Freshly harvested samples were kept in a refrigerated room overnight and transported the next day to the University of Arkansas rice processing laboratories. Rough rice samples were air-dried to ≈12% MC and then size-fractionated using a precision sizer (CarterDay Co., Minneapolis, MN) to large, medium, and thin thickness fractions. Only rice kernels of the medium thickness fraction (1.69–1.72 mm of milled rice) were used in this study to provide a uniform kernel size across samples because kernel size tends to affect uniaxial compression tests results (Matsue et al 2001; unpublished data).

Preliminary Milling Experiment

Because rice cultivars mill differently (i.e., milling duration varies between cultivars to achieve a target DOM), a preliminary milling experiment was conducted to determine the milling duration necessary to achieve target DOM levels of 0.2, 0.3, 0.4, 0.5, and 0.6% (as-is basis) SLC for each rice cultivar at each location and harvest MC. Initially, 150 g of rough rice was dehulled using a dehusker (THU-35, Satake, Hiroshima, Japan) and milled for 10, 20, 30, 40, or 50 sec in a McGill No. 2 mill (RAPSCO, Brookshire, TX). A double-tray sizing device (GrainMan Machinery, Miami, FL) was used to separate head rice from the broken kernels and the milled rice SLC was determined using a Soxtec system (Avanti 2055, Foss North America, Eden Prairie, MN). The relationship between milling duration and SLC was determined for each cultivar at each location and harvest MC. Depending on the SLC and milling duration relationship for each cultivar, a set of milling durations was calculated to achieve our target SLC.

Rice Milling and Head Rice Yield (HRY) Determination

Rough rice from each cultivar (150 g, ≈12% MC) was dehulled using a dehusker (THU-35, Satake, Hiroshima, Japan). The resulting brown rice was then milled using a McGill No. 2 mill (RAPSCO) for various durations, based on the results of the preliminary milling experiment, to achieve the target SLC of 0.2, 0.3, 0.4, 0.5, and 0.6% (Table I). The double-tray sizing device was used to separate head rice from the broken kernels. HRY was calculated by dividing head rice weight by 150 g and is reported as the mean values of duplicate analyses.

Milled Rice Whiteness

The degree of whiteness of milled rice samples was determined in duplicate with a Kett whiteness tester specifically designed to measure whiteness of rice (model C-300-3, 1-8-1 Minami–Magome, Ota-Ku, Tokyo, Japan). The Kett whiteness tester was calibrated with the international whiteness standard using a calibration plate. Rice whiteness values were determined as a reflective index of the sample surface: the higher the value, the whiter the milled rice is.

Protein Content

Milled rice protein content for various SLC was determined using Approved Method 46-11A (AACC International 2000). Nitrogen content was measured in duplicate by the Kjeldahl procedure; protein content of rice flour was calculated by multiplying the nitrogen content by 5.95.

Surface Lipid Content

Milled rice SLC was determined in duplicate using a Soxtec system (Avanti 2055, Foss North America, Eden Prairie, MN) according to Approved Method 30-20 (AACC International 2000) by modifying the washing duration from 30 to 20 min using petroleum ether as described by Matsler and Siebenmorgen (2005).

Instrumental Texture Measurements

A water-to-rice ratio of 2:1 was used for rice cooking. Rice was cooked using a miniature precision rice cooker consisting of a glass cooking vessel (200 mL in volume and semispherical) with a glass top and a heating mantle (TM 102, Glas-Col, Terre Haute, IN) with a temperature controller (89000-10, Eutech Instruments Pte Ltd, Singapore) for 20 min. Maximum cooking temperature was set at 98.5 ± 1°C as indicated by a thermocouple inserted through the glass top and placed in contact with the bottom surface of the cooking vessel during cooking. Cooked rice was conditioned for 5 min and kept warm (50°C) using a temperature-controlled mantle during cooked rice texture measurements. The cooking conditions were identical for all rice samples to eliminate differences in cooked rice texture properties due to the cooking method. Cooked rice texture attributes were determined by a uniaxial single compression method using a TA-XT2 Plus texture analyzer (Texture Technologies, Scarsdale, NY). Ten cooked rice kernels placed on a nonlubricated flat aluminum plate were compressed using a 50-kg load cell to leave a gap of 0.3 mm between the two compression plates at the bottom of the compression cycle. The crosshead was also stopped for 5 sec at its maximum travel distance before returning to an anvil separation of 20 mm. The crosshead speed was set to 5 mm/sec during the downward stroke of the compression plate and 0.5 mm/sec during its upward stroke. Texture attributes were obtained using texture exponent software (Stable Microsystems, v.1.0.0.92, Surrey, England). Maximum compression force (N) was used as an indicator of cooked rice firmness. Adhesion energy (area under the curve, N·sec) measured during the upward stroke of the compression plate was an indicator for cooked rice stickiness. Samples were cooked in duplicate and six measurements were taken for each cook.

TABLE I
Milling Quality of Rice Cultivars Francis and Wells Harvested at Various Moisture Contents (MC %) from Stuttgart, AR, and Essex, MO, Locations[a,b]

	Stuttgart, AR					Essex, MO				
Cultivar	Harvest MC (%)	DOM (SLC)	Milling (sec)	% Bran Removed	HRY	Harvest MC (%)	DOM (SLC)	Milling (sec)	% Bran Removed	HRY
Francis	14.7	0.6	15	10.9a	62.5a	12.8	0.6	25	10.5c	36.7a
		0.5	16	11.7b	62.4a		0.5	31	12.5b	35.7a
		0.4	30	12.5ab	62.1ab		0.4	36	12.6ab	34.7a
		0.3	35	12.7ab	60.4ab		0.3	42	12.7ab	34.1a
		0.2	45	13.3a	59.1b		0.2	48	13.3a	34.0a
Francis	21.8	0.6	30	10.3a	71.2a	21.0	0.6	23	11.2b	67.9a
		0.5	34	11.0a	69.8ab		0.5	28	12.1b	67.5a
		0.4	38	11.4a	69.1ab		0.4	33	12.3b	65.5ab
		0.3	42	12.4a	67.9ab		0.3	38	12.5ab	65.3ab
		0.2	47	12.6a	67.4b		0.2	42	13.7a	63.5b
Wells	13.7	0.6	22	11.8c	68.8a	16.3	0.6	26	10.9c	67.3a
		0.5	28	13.1bc	66.8ab		0.5	31	11.5bc	65.6ab
		0.4	33	13.6ab	66.5b		0.4	36	11.9abc	64.1ab
		0.3	38	13.7ab	66.0cb		0.3	40	12.9ab	63.7b
		0.2	43	14.8a	64.1c		0.2	45	13.3a	63.0b
Wells	21.4	0.6	28	10.7d	70.9a	22.0	0.6	22	11.3a	61.9a
		0.5	33	11.3dc	69.5ab		0.5	27	11.9a	61.6a
		0.4	38	11.8bc	68.4ab		0.4	32	12.1a	61.2a
		0.3	43	12.2ab	67.1b		0.3	37	12.8a	59.8a
		0.2	48	12.9a	66.5b		0.2	42	13.2a	59.3a

[a] Degree of milling (DOM), surface lipid content (SLC), and head rice yield (HRY) of rice during the milling process.
[b] Mean values of HRY, % bran removed for each cultivar harvested at similar harvest MC levels and milled to various DOM levels followed by different letters are significantly different according to least significant difference (LSD) at $P < 0.05$.

Cooked Rice Moisture Content (MC)

Triplicate measurements of cooked rice MC were taken after each cook. Cooked rice (≈5 g) was incubated in a drying oven (Precision Scientific, Winchester, VA) at 130°C for 24 hr. Cooked rice MC was calculated as the amount of water removed from each cooked rice sample after the incubation period.

Removal of Milled Rice SLC Before Cooking

Rice samples (Francis harvested at 14.7 and 21.8% MC) were milled to target surface lipids of 0.2, 0.4, and 0.6% SLC (milling procedure as described earlier). Milled rice samples were washed using hexane (EM-Science HX 0298-1) in a 1:2 (w/v) ratio of rice-to-hexane for 10 sec, after which samples were wiped and air-dried for 1 hr (Marshall et al 1990) with modification of the treatment duration. This treatment was performed to partition the effect of lipid and protein removal during milling on cooked rice texture properties. SLC and protein content were measured before and after hexane treatment, as described earlier. Rice samples were cooked in duplicate, and the texture attributes of the cooked rice were determined according to the methods described earlier.

Statistical Analysis

A full-factorial design of 2 × 2 × 2 × 5 representing the harvest location, harvest MC, cultivar, and DOM (SLC) was used in this study. ANOVA was performed using JMP (release 5.1.2, SAS Institute, Cary, NC) to determine the significance of differences. Least significant difference (LSD) at a 5% level of probability was used to identify significant differences in rice milling quality and instrumental texture properties among rice lots harvested at similar MC and milled to various levels (SLC). Differences in the instrumental texture properties of rice lots harvested at various MC and milled to similar SLC was also determined.

RESULTS AND DISCUSSION

Milling durations of the rice samples ranged from 15 sec (Francis harvested at 14.7% MC) to 48 sec (Francis harvested at 12.8% MC) to achieve milled rice with SLC of 0.6 and 0.2%, respectively (Table I). Results indicated that milling durations varied for the same cultivar when harvested at various MC levels as well as from different locations. For instance, Francis harvested from Stuttgart at 14.7% MC required a shorter milling duration (15 sec) to achieve SLC of 0.6% than Francis harvested at 21.8% MC (30 sec). Whereas, the opposite was found for Francis harvested from Essex, MO (Table I). Similar trends were observed for Wells. This clearly illustrates "millability" variability and its unpredictability.

As expected, HRY decreased with increasing DOM (Table I). HRY range was 34.0–71.2% for Francis harvested from Essex, MO, and Stuttgart, AR, locations. HRY results indicated that cultivars harvested at low MC (with the exception of Wells harvested from Essex, MO) had lower HRY than cultivars harvested at higher MC. Several factors probably affect the maximum possible HRY associated with a harvested rice lot even when dried under the gentlest conditions. For instance, Siebenmorgen et al (1992) reported a decrease in HRY for rice samples harvested at high MC (due to a higher percentage of less mature kernels) and low MC (due to fissures that are formed in the field due to rapid moisture adsorption). Although fissuring was not measured here, the decrease in HRY for samples harvested at low MC (12.8, 13.7, and 14.7%) compared with those harvested at high MC (21.0, 21.4, and 21.8%) indicates that rice samples that were dried mostly in the field could have been subjected to a wide range of temperatures and humidities (in contrast to samples dried in our laboratories) that increased kernel fissuring and thus decreased HRY.

TABLE II
Protein and Surface Lipid Content (SLC) of Francis and Wells Rice Cultivars Harvested at Various Moisture Contents (MC %) and Milled to Various Degrees of Milling (DOM)[a,b]

Cultivar and DOM (SLC)		Stuttgart, AR Harvest MC (%)	Protein Content	Measured SLC	Degree of Whiteness	Essex, MO Harvest MC (%)	Protein Content	Measured SLC	Degree of Whiteness
Francis	0.6	14.7	7.2a	0.59a	34.2a	12.8	7.2a	0.64a	35.8a
	0.5		7.4a	0.49b	35.9b		7.2a	0.51b	37.6b
	0.4		7.2a	0.41c	38.2c		7.1a	0.41c	40.0c
	0.3		6.7b	0.29d	41.1d		7.1a	0.32d	43.0d
	0.2		6.5b	0.20e	44.4e		7.1a	0.23e	46.7e
				$R^2 = 0.983$				$R^2 = 0.956$	
Francis	0.6	21.8	8.1a	0.62a	33.1a	21.0	6.5a	0.65a	34.2a
	0.5		7.8b	0.52b	35.1b		6.4a	0.53b	36.2b
	0.4		7.9b	0.43c	38.6c		6.4a	0.40c	38.6c
	0.3		7.3c	0.31d	42.4d		6.5a	0.29d	41.3d
	0.2		7.3c	0.20e	46.8e		5.9b	0.20e	44.3e
				$R^2 = 0.99$				$R^2 = 0.981$	
Wells	0.6	13.7	7.6a	0.59a	36.1a	16.3	7.5a	0.60a	33.1a
	0.5		7.5a	0.52b	37.7b		7.4a	0.51b	36.2b
	0.4		7.5a	0.41c	39.6c		7.4a	0.41c	38.2c
	0.3		6.9b	0.33d	42.0d		7.5a	0.33d	40.3d
	0.2		7.2ab	0.18e	44.5e		6.8b	0.25e	42.6e
				$R^2 = 0.993$				$R^2 = 0.994$	
Wells	0.6	21.4	7.9ab	0.59a	33.8a	22.0	7.7a	0.61a	32.5a
	0.5		7.8b	0.50b	35.9ab		7.6bc	0.50b	34.1b
	0.4		8.1a	0.42c	38.3c		7.6c	0.38c	36.1c
	0.3		7.9b	0.31d	41.2d		7.7ab	0.27d	38.5d
	0.2		7.1c	0.20e	44.4e		7.3d	0.18e	41.4e
				$R^2 = 0.999$				$R^2 = 0.976$	

[a] Mean values of protein content and SLC of the same cultivar and harvest MC milled to 0.2–0.6% SLC followed by different letters are significantly different according to least significant difference (LSD) at $P < 0.05$.
[b] Coefficient of determination (R^2) of measured SLC vs. degree of whiteness.

This illustrates that the impact of MC at harvest and drying practices (rice dried in the field vs. drying under gentle drying conditions) in determining the physical properties of milled rice. The low HRY for Francis harvested at 12.8% MC compared with other samples was possibly due to blast or sheath blight noticed during harvesting of that particular cultivar. Infected rice kernels have been reported to be drier and thinner than those from disease-free plants and also, more likely, to be unfilled, chalky, and fissured (Candole et al 2001).

Table I also shows the percentage of bran removal from rough rice during the milling process. Percent of bran removed ranged from 10.3 to 14.8%. Because most of the lipids are localized on the outer caryopsis coat, aleurone, and subaleurone layers of rice kernels, milling to longer durations consequently resulted in removal of a greater amount of SLC. As expected, milling to a lower SLC significantly ($P < 0.05$) decreased protein content across samples used in this study (Table II). This is because the outer layers of a rice kernel are disproportionately rich in protein.

The whiteness of the samples ranged from 33.1 to 46.8 for Francis and from 32.5 to 44.5 for Wells after milling to various DOM (SLC). Milled rice whiteness was correlated to the measured SLC (DOM) with coefficients of determination (R^2) ranging from 0.955 to 0.998, indicating that both SLC and whiteness values are satisfactory indicators of rice DOM. Moreover, milled rice whiteness was slightly influenced by rice harvest MC. For example, samples harvested at low MC had slightly higher whiteness values (although not significant for most of the samples) than those harvested at high MC (Table II). This could be due to the fact that high harvest MC samples were slightly higher in protein than corresponding low harvest MC samples. This is not surprising because high harvest MC samples would have a greater percentage of slightly immature kernels, which are known to be richer in protein.

Table III shows the SLC and protein content of rice samples (Francis samples harvested at 14.7 and 21.8% MC) before and after hexane treatment. This treatment was conducted to partition out the effect of lipid and protein removal during milling on the texture properties of cooked rice. The effect of the hexane treatment on cooked rice texture will be discussed later. Results indicated that the hexane treatment significantly ($P < 0.05$) reduced SLC of milled rice. For instance, removal of SLC from Francis samples harvested at 14.7% MC reduced the SLC from 0.2, 0.4, and 0.6 to 0.03, 0.04, and 0.08% (±0.01), respectively. As expected, hexane treatment had a minimal effect ($P > 0.05$) on milled rice protein content. These results show that we were successful in removing most lipids without also removing proteins, which allows us to discuss specific roles of proteins and lipids on rice texture.

Cooked rice MC ranged from 67.81 to 70.50% (Table IV). Milling to high degrees (based on SLC) resulted in increasing cooked rice water uptake (although the increase was not significant [$P > 0.05$] for some samples). This implies that the outermost layers of lightly milled rice kernel tend to restrict water migration in the kernel during cooking. The decrease in water uptake could be due to the decrease in overall protein content. The increase in cooked rice MC with increasing degree of milling is in agreement with Yanase et al (1984), who indicated that water absorption is decreased with increasing protein content in rice.

Table IV presents cooked rice texture properties of cultivars harvested from Stuttgart, AR, and Essex, MO. Cooked rice firmness ranged from 90.12 to 110.51 N for Francis and from 93.52 to 111.26 N for Wells. Results indicate that increased rice milling (i.e., decreasing SLC) decreased cooked rice firmness. Rice samples milled to the lowest (0.2%) SLC were significantly ($P < 0.05$) softer than those milled to the highest (0.6%) SLC. However, the difference was not significant ($P > 0.05$) for Francis harvested from Essex, MO. We have stated earlier that with increasing milling, a disproportionate loss of proteins occurs due to the fact that the outermost layer of the rice endosperm are rich in proteins compared with rest of the kernel. Derycke et al (2005) reported a decrease in cooked rice firmness when milled rice was cooked in the presence of DTT, a strong reducing agent. Therefore, the decrease in cooked rice firmness associated with greater milling could be a result of the lesser amount of proteins present on the surface of these kernels. Our results are also in accordance with Kim et al (2001), who suggested that changes in the sensory texture properties of cooked rice as well as in the pasting properties of rice flour are mainly due to differences in proximate composition.

In addition to the role of proteins in determining water absorption during cooking, lipids can also play a role in kernel water uptake. In an intact rice kernel, lipids are predominantly located in the bran layer, which is progressively removed during milling. Banks and Greenwood (1975) indicated that lipids in the rice endosperm tend to form an inclusion compound with amylose. Several authors have referred to these complexes as lipid amylose complexes (LAM) and lipid amylopectin (LAP) complexes (Vandeputte et al 2003). These complexes are also believed to restrict starch granule swelling during heating and prevent leaching of amylose during gelatinization (Eliasson and Krog 1985; Eliasson et al 1988). Moreover, these complexes are reported to form with leached out starch molecules during cooking, as indicated by the influence of lipids on starch pasting profiles in the presence of a sufficient amount of water (Hamaker and Zhang 2003). Thus, decreasing

TABLE III
Changes in Milled Rice Protein and Surface Lipid Content (SLC) and Cooked Rice Firmness and Stickiness of Francis Samples Due to Hexane Treatment[a,b,c]

		SLC			Protein Content		
Harvest MC %	**Hexane**	**0.2%**	**0.4%**	**0.6%**	**0.2%**	**0.4%**	**0.6%**
21.8	No	0.18a	0.31a	0.51a	6.5a	6.5a	6.9a
	Yes	0.03b	0.04b	0.07b	6.4a	6.4a	6.6a
14.7	No	0.20a	0.39a	0.56a	6.8a	7.0a	7.3a
	Yes	0.03b	0.04b	0.08b	6.7a	6.9a	7.1a
		Firmness			**Stickiness**		
21.8	No	82.74	90.73	89.16	6.23	6.92	6.72
	Yes	83.88	87.93	87.50	7.18	6.96	5.42
14.7	No	96.57	103.32	104.39	10.32	9.27	8.03
	Yes	93.57	102.23	101.64	8.51	8.60	7.11

[a] SLC and MC represent the target surface lipid content and moisture content, respectively. Samples with hexane treatment (Yes) and samples not treated (No).
[b] Mean values of milled rice protein content and SLC, milled to similar SLC, with and without hexane treatment, followed by different letters are significantly different according to least significant difference (LSD) at $P < 0.05$.
[c] For each harvest MC, mean values of cooked rice firmness and stickiness for rice milled to similar SLC, with and without hexane treatment, were not significantly different according to least significant difference (LSD) at $P < 0.05$.

SLC could result in decreasing the ability of lipids to complex with amylose or amylopectin during cooking, and allow the starch to swell more readily at least at the grain surface, thereby decreasing cooked rice firmness. This is further supported by decreased cooked rice firmness of the SLC removed samples using hexane treatment (Table III). Moreover, the increase in cooked rice MC after SLC removal supports this explanation of the role lipids play in determining water uptake and rice texture and is in agreement with Eliasson and Krog (1985) and SeneViratne and Biliaderis (1991), who indicated that amylose lipid complexes tend to decrease water uptake.

Table IV also shows the effect of harvest MC (HMC) on cooked rice firmness of Francis and Wells cultivars harvested in Stuttgart, AR, and Essex, MO. Samples harvested at high MC (21.0–22.0%) were significantly ($P < 0.05$) less firm than samples harvested at low MC (12.8–16.3%), except for Wells harvested in Stuttgart, AR. These results seem to be in disagreement with Champagne et al (2005), who reported that early harvested rice (high HMC) was harder than late harvested samples. However, the range of HMC tested by Champagne et al (2005) was 25.9–19.6%, while HMC in the present study was 12.8–22%. The differences in firmness associated with HMC could stem from differences in drying conditions. Samples harvested at high MC were gently dried (i.e., air-dried inside our laboratories) compared with samples harvested at low MC (i.e., mostly dried in the field) where the kernel was subjected to a wider range of temperatures and overall higher temperatures. This indicates that although lipids and proteins explained, to some extent, differences in cooking and texture properties, postharvest factors such as HMC and drying also affect cooked rice texture properties (Siebenmorgen and Meullenet 2004). For instance, differences in drying regimes reportedly affect various physical properties of rice (Meullenet et al 1999) including cooked rice texture.

The effect of harvest MC on cooked rice stickiness is also presented in Table IV. When milled to a high DOM (SLC 0.2%), rice harvested at low MC was significantly ($P < 0.05$) stickier (except Wells harvested from Stuttgart, AR) than that harvested at high MC. Stickiness values ranged from 5.96 to 13.18 N·sec for Francis and from 5.39 to 12.01 N·sec for Wells (Table IV). Results indicate that instrumental texture stickiness of cooked rice increased (although not always significantly) with milling degree across cultivars, locations, and harvest MC. Greater stickiness values are correlated with lower lipid and protein contents and with higher water uptake during cooking. These changes are probably due to the significant decrease in protein and SLC with increasing DOM (Table II). As mentioned earlier, proteins and lipids tend to form complexes with the leached out starch. Therefore, the decrease in kernel protein and surface lipid contents with milling can decrease the formation of these complexes and consequently affect cooked rice texture properties. The increase in cooked rice stickiness found in hexane-treated samples (although not significant at $\alpha = 0.05$) compared with nontreated samples (Table III), as well as the increase in moisture uptake during cooking with increasing DOM provides support for this explanation.

CONCLUSIONS

Milling rice to various DOM affected milled rice HRY, whiteness, chemical composition, water uptake during cooking, and cooked texture properties. Milling to lower SLC decreased cooked rice firmness and increased cooked rice stickiness across locations, cultivars, and harvest MC. Protein and lipid contents in milled rice decreased with increasing DOM. During cooking, proteins and lipids are believed to interact with starch, forming protein-starch and lipid-starch complexes that tend to restrict water absorption

TABLE IV
Mean Values of Firmness, Stickiness, and Cooked Rice MC of Rice Cultivars Francis and Wells Milled to Various Degrees[a,b,c]

Cultivar and DOM (SLC)	Firmness		Stickiness		Cooked Rice MC	
			Stuttgart, AR			
Francis	**HMC 14.7%**	**HMC 21.8%**	**HMC 14.7%**	**HMC 21.8%**	**HMC 14.7%**	**HMC 21.8%**
0.6	110.51aA	98.61aB	8.84bA	6.55aB	68.85cA	67.90cA
0.5	107.01abA	96.81aB	9.80bA	7.45aB	68.95cA	68.40bcA
0.4	105.12bcA	95.60abB	8.54bA	6.74aA	69.22bcA	69.09bA
0.3	102.24cA	92.97abB	9.37bA	8.16aA	69.58abA	70.18aA
0.2	90.12dA	90.38bA	13.18aA	6.59aB	69.74aA	70.50aA
Wells	**HMC 13.7%**	**HMC 21.4%**	**HMC 13.7%**	**HMC 21.4%**	**HMC 13.7%**	**HMC 21.4%**
0.6	108.74aA	109.13aB	5.39cA	6.14cA	69.04aA	68.54aA
0.5	102.98aA	104.84abB	7.25bcA	7.78bcA	69.02aA	68.72aA
0.4	102.55aA	104.04bcB	7.39bA	7.26cA	69.05aA	69.10aA
0.3	101.64aA	99.30cdB	9.33aA	10.34aA	69.29aA	69.45aA
0.2	93.52bA	97.35dB	9.49aA	9.60abA	69.26aA	69.24aA
			Essex, MO			
Francis	**HMC 12.8%**	**HMC 21.0%**	**HMC 12.8%**	**HMC 21.0%**	**HMC 12.8%**	**HMC 21.0%**
0.6	102.95aA	95.66aB	5.96cA	7.01aA	67.81bA	68.37bA
0.5	102.27aA	94.14aB	7.74bA	7.69aA	67.96bB	68.96bA
0.4	101.68aA	92.22aB	8.39abA	7.22aA	68.34abA	69.22abA
0.3	100.02aA	92.75aB	9.83aA	8.98aA	68.80aB	70.03aA
0.2	99.43aA	91.04aB	10.08aA	8.36aB	69.06aA	69.15abA
Wells	**HMC 16.3%**	**HMC 22.0%**	**HMC 16.3%**	**HMC 22.0%**	**HMC 16.3%**	**HMC 22.0%**
0.6	111.26aA	101.34aB	7.29bA	6.69aA	68.48bA	68.08bA
0.5	102.38cA	98.13abB	8.03bA	8.05aA	68.73bA	69.15aA
0.4	101.24cA	96.28bB	7.32bA	7.81aA	69.30aA	69.37aA
0.3	103.63bcA	96.69bB	9.19bA	7.65aA	69.47aA	69.49aA
0.2	107.95abA	94.94bB	12.01aA	7.94aB	69.65aA	69.66aA

[a] Degree of milling (DOM), surface lipid content (SLC), and harvest moisture content (HMC) of rice.

[b] Mean values of firmness, stickiness, and cooked rice MC of the same cultivar and MC at harvest milled to different DOM followed by different letters (lowercase) are significantly different according to least significant difference (LSD) at $P < 0.05$.

[c] Mean values of firmness, stickiness, and cooked rice MC of the same cultivar harvested in the same location and milled to similar DOM at low or high harvest MC followed by different letters (uppercase) are significantly different according to least significant difference (LSD) at $P < 0.05$.

during cooking by preventing inner constituents of rice kernels from fully interacting with water. For low DOM rice, this results in lower cooked rice moisture absorption during cooking and thus increased cooked rice firmness. The lack of significant changes in rice texture properties after hexane treatment (removal of most surface lipids) indicates that the rice proteins probably play a greater role than lipid in dictating the texture properties of cooked rice.

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