Surface Lipid and Free Fatty Acids (FFA) Content of Head and Broken Rice Produced by Milling After Different Drying Treatments

M. A. Monsoor,[1] A. Proctor,[1,2] and T. J. Siebenmorgen[1]

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ABSTRACT

The surface lipids and free fatty acids (FFA) content of head and broken rice samples generated through milling after various drying treatments were studied. Long grain cultivars Francis, Wells, and Cypress, and medium grain cultivar Bengal were dried under three air conditions (mild 25°C, 50% rh; moderate 45°C, 40% rh; and stressed 65°C, 20% rh) for two durations (10 and 30 min). Immediately after drying, the rough rice samples were placed in a conditioning chamber to continue drying slowly to ≃12.5% moisture content (MC), which occurred within three to five days. After dehulling, a McGill No. 2 mill was used to mill the samples for 30 sec. The head rice yield (HRY) for all rice samples were within the range of 40–68%. Rice surface lipid was extracted with isopropanol (IPA) and the lipid and FFA content of the IPA extracts were determined. Broken rice kernels had significantly greater surface lipid and FFA content than head rice kernels. The surface FFA contents of broken kernels were within the range of 0.045–0.065% of broken rice mass, while that of head rice was 0.027–0.040%. Broken rice had greater *b* values indicating greater yellow color than did head rice.

Rice quality is partially determined by weather conditions during production but is largely controlled by harvesting methods and postharvest practices. These include rough rice drying and milling. Rice is usually harvested as rough rice at ≈16–22% moisture content (MC, wb) and is typically dried to ≈12–13% MC before storage or milling. Before milling, rough rice is dehulled to form brown rice. Milling removes bran from brown rice to produce white rice or milled rice. The value of milled rice is based on the milled rice yield (MRY), which is the weight percentage of rough rice that remains as head rice and brokens and the head rice yield (HRY), which is the weight percentage of rough rice remaining as head rice. Head rice represents milled kernels of rice having length that is 75% or more of the original brown rice kernel length. The head rice is used as table rice, and broken rice is used to produce low-valued processed foods.

Milled rice surface lipid content is an important quality parameter because rice surface acylglycerols are hydrolyzed to free fatty acid (FFA) through lipase action (Tanako 1989; Ohta et al 1990) and further oxidize to form off-flavors (Yasumatsu et al 1966; Aibra et al 1986; Tanako 1993). The brewing industry, a major rice user, considers FFA content as an indicator of rice quality and currently does not accept milled rice with FFA levels >0.1% rice. Head rice is preferred in brewing, even though brokens are less expensive, because brokens are thought to be associated with off-flavor development in beer although no studies have been conducted to show this. Recently, Monsoor and Proctor (2003) found that commercially milled broken rice had significantly greater surface lipid contents than head rice. Commercially milled broken rice also showed a greater rate of lipid hydrolysis and oxidation relative to head rice but no studies have reported the cause.

The effects of drying and milling on HRY have been studied extensively. Drying can produce stress in the rice kernel, which can cause kernels to fissure (Sharma and Kunze 1982; Cnossen and Siebenmorgen 2000). Kernel fissuring results in breakage during milling and consequently lowers HRY. According to Arora et al (1973), the drying air temperature should be <53°C to minimize the effect of thermal expansion on rice fissuring. The transition of rice starch from a glassy to rubbery stage during rough rice drying has played an important role in rice fissuring and drying rate (Cnossen and Siebenmorgen 2000; Cnossen et al 2002). Fan et al (2000) found that during heated-air drying, the drying air condition, and drying duration significantly affected the proportion of head and brokens in milled rice. The proportion of head and brokens is also determined by the proportion of thick and thin kernels in the population (Sun and Siebenmorgen 1993). Chen et al (1998, 1999) conducted research on the milling performance of long and medium grain rice in commercial milling systems and found that the surface lipid content of milled rice varied significantly across kernel thickness. However, the effect of drying conditions and drying duration on the lipid quality of head and broken rice has not been studied. Therefore, the objective of this study was to determine the effect of drying conditions, drying duration, and milling on the surface lipid and free fatty acid content of milled head and broken rice.

MATERIALS AND METHODS

Rice Samples

Rice cultivars Bengal (medium grain), and Cypress, Francis, and Wells (long grains) with harvest moisture contents of 20.2, 19.2, 22.1, and 18.7%, respectively, were obtained from the University of Arkansas Rice Research and Extension Center at Stuttgart, AR, in 2002. Immediately after harvest, samples were cleaned with a dockage tester (Carter-Day Co., Minneapolis, MN) and stored at 4°C in plastic containers for rough rice drying studies.

Rice Drying

The rough rice samples were air-dried under three different conditions: mild (25°C, 50% rh), corresponding to 11.3% rough rice equilibrium moisture content (EMC) as calculated by the Modified Chung Equation (ASAE 1998); moderate (45°C, 40% rh), corresponding to 8.7% EMC; and severe (65°C, 20% rh) corresponding to 4.9% EMC. Drying air relative humidity and temperature were controlled with a Climate-Lab-AA unit (Parameter Generation and Control, Black Mountain, NC), which was used to circulate conditioned air through perforated trays of the drying chamber. Each drying chamber consisted of sixteen 15- by 25-cm perforated trays. Temperatures and relative humidities in the drying chambers were monitored by a dew point hygrometer (General Eastern Hygro-M2, Woburn, MA). The drying duration was either 10 or 30 min to produce rough rice with various kernel MC gradients. For each rice cultivar, the drying trials comprised six drying treatments resulting from the combination of three drying air conditions and two drying durations. Each drying treatment was replicated three times. For each drying treatment, ≈200 g of rough rice was placed uniformly into each of the 16 trays of the

[1] Department of Food Science, University of Arkansas, 2650 N. Young Avenue, Fayetteville, AR 72704.

[2] Corresponding author. Phone: 479-575-2980. Fax: 479-575-6936. E-mail: aproctor@uark.edu

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drying chamber. For each replicate, four trays of the drying chamber were used to dry rough rice samples from each of the four cultivars. After each drying duration, the samples were placed in a conditioning chamber at 21°C and 50% rh, corresponding to a rough rice EMC of 12.5%, to equilibrate slowly and to prevent any rapid state transition immediately after drying. According to Cnossen et al (2000), the high internal MC gradient in the kernel produced by rough rice drying caused a rapid state transition immediately after drying and reduced HRY. Such a rapid state transition could be prevented by placing the heated rice in the 21°C chamber. The condition in this second chamber allowed the samples to continue drying slowly to ≈12.5% MC, which occurred within three to five days. After conditioning, rough rice samples were placed in sealed plastic bags and stored at 4°C until milling.

Rough Rice Moisture Content

The initial moisture content (IMC) before drying and the loss in MC due to drying of the rough rice samples were measured using an oven drying MC determination method (Jindal and Siebenmorgen 1987), in which 15 g of rough rice were dried in a oven at 130°C for 24 hr. Three measurements were made for each sample.

Rice Dehulling and Milling

Rough rice samples were removed from storage at 4°C for three to four days and allowed to reach 22°C before milling. From each cultivar, drying air condition, and replicate combination, 150-g rough rice subsamples were hulled in a rice sheller (Satake Engineering Co., Tokyo, Japan). The resultant brown rice was then milled for 30 sec using a McGill No. 2 mill (Rapsco, Brookshire, TX) with a 1,500-g mass positioned on the mill lever arm 15 cm from the centerline of the milling chamber. An aspirator (Seedboro Equipment Co. Chicago, IL) was used to remove the loose bran from the milled rice.

Head Rice Yield

The head rice within the milled rice fraction was separated using a double-tray shaker table (Grainman, Grain Machinery, Miami, FL) with both trays having indented holes to separate the broken kernels from the head rice. The hole sizes of the trays for long grain and medium grain rice samples were 4.76 and 3.96 mm, respectively. The HRY was calculated by expressing the milled rice (head rice) mass as a percentage of the original 150-g rough rice mass.

Surface Lipid and FFA Content of Head and Broken Rice

Surface lipid contents of the milled head and broken rice samples were extracted with 4 mL of isopropanol (IPA) by vortexing 5 g of rice sample and surface lipid, and FFA content of the extracts were determined colorimetrically (Lam and Proctor 2001). Measurements of surface lipid and FFA contents were made in triplicate for head rice and brokens sample.

Hunter *b* Color Values of Head and Broken Rice

Hunter *b* values of head and broken rice samples were measured using a colorimeter (model DP 301, Minolta, Osaka, Japan). The rice samples were placed on a white paper on the desk top and the measuring arm of the hand-held color instrument was placed in contact and above the milled head and broken rice samples to take the color measurements. This procedure allowed a consistent difference between the rice samples and the measuring arm of the instrument. This approached was used to avoid any variability in measurements due to differences in size and shape of the head and broken rice samples. Three measurements were made for each rice sample. The Hunter *b* values, which are an indication of the yellowness of the rice, were measured to indicate the color of the head and broken rice kernels. Preliminary studies showed that the Hunter *b* value correlated with milled rice surface lipid content (*unpublished data*). The colorimeter was calibrated with a reference white plate provided with the instrument before each measurement was made.

Statistical Analysis

Analysis of variance was conducted using JMP v. 5.0.1 (SAS Institute, Cary, NC). Student's *t*-test was used to differentiate mean values with significance defined at $P < 0.05$.

RESULTS AND DISCUSSION

Moisture Content of Rough Rice

The MC values of the rice cultivars before and after each drying treatment are presented in Table I. Francis had greater initial and final MC values relative to the other rice cultivars. Under the mild drying condition (25°C, 50% rh), very little MC reduction was observed (0.46–1.46 percentage points). As the drying conditions changed from mild to more severe, the MC reduction increased significantly, as would be expected. Under the most severe of the drying treatments, MC reduction was greatest (3.75–5.20 percentage points). The total MC reductions under the most severe drying treatment (65°C /20% rh 30 min) for Bengal, Francis, Wells, and Cypress were 4.2, 5.2, 3.7, and 4.2 percentage points, respectively.

Head Rice Yield

The HRY values of the rice cultivars from milling after various drying treatments are presented in Table II. The HRY values obtained across all rice cultivars dried under different treatments were 40.8–67.9%. The most severe drying condition (65°C, 20%rh for 30 min) significantly reduced the HRY for all cultivars. Fan et al (2000) also found that drying condition and drying duration had significant interactive effects on HRY reduction during drying. The reductions in HRY due to the most severe drying condition (65°C, 20%rh for 30 min) when compared with the mildest drying condition (25°C, 50%rh for 10 min) for Bengal, Francis, Wells,

TABLE I
Moisture Contents (% wb) of Rough Rice Cultivars Before and Immediately After Drying[a,b]

Drying Treatment[c]	Bengal	Francis	Wells	Cypress
Undried[d]	17.9 ± 0.08a[e]	21.8 ± 0.14a	16.9 ± 0.03a	17.8 ± 0.18a
25°C/50% rh; 10 min	17.2 ± 0.09b	21.1 ± 0.05b	16.4 ± 0.37b	17.4 ± 0.13b
25°C/50% rh; 30 min	17.0 ± 0.11bc	20.4 ± 0.11c	16.0 ± 0.15bc	17.1 ± 0.26bc
45°C/40% rh; 10 min	16.7 ± 0.11c	20.3 ± 0.09c	15.9 ± 0.25c	16.8 ± 0.01c
45°C/40% rh; 30 min	16.3 ± 0.09d	20.0 ± 0.25cd	15.6 ± 0.12d	16.3 ± 0.23d
65°C/20% rh; 10 min	16.0 ± 0.08e	19.5 ± 0.18d	15.2 ± 0.11e	16.0 ± 0.20d
65°C/20% rh; 30 min	13.7 ± 0.14f	16.6 ± 0.20e	13.2 ± 0.24f	13.6 ± 0.28e

[a] All samples were slowly dried to ≃12.5% after drying.
[b] Data are expressed as means ± standard deviations; three oven moisture content measurements for each replicate; results are means of nine measurements.
[c] Temperature/relative humidity of the drying air; drying duration.
[d] Undried data of moisture contents before drying (means of three measurements).
[e] Values followed by the same letters in the same column are not significantly different ($P < 0.05$).

and Cypress were 20.8, 7.5, 23.0, and 11.1 percentage points, respectively. Bengal and Wells were more sensitive to the most severe drying condition relative to Francis and Cypress. This could have been due to the lower IMC values and higher proportion of thin kernels in Bengal and Wells cultivars relative to Francis and Cypress.

The primary mechanism for bran removal in the McGill mill is kernel-to-kernel abrasion that may be affected by the size and thickness of the kernels. Reid et al (1998) found that kernel thickness affected the relationship between HRY and degree of milling during milling in a McGill No. 2 mill. Matthews and Spadaro (1976) also found that long grain milled rice breakage was greater for the thinner than for the thicker fractions. Sun and Siebenmorgen (1993) also found that when the thinnest thickness fractions of rice were removed, the HRY of the remaining kernels were greater than that of the unfractionated control.

TABLE II
Effect of Various Drying Treatments on Head Rice Yields (HRY) of Different Rice Cultivars[a]

Rice Cultivar	Drying Treatment[b]	HRY (%)
Bengal	25°C/50% rh; 10 min	63.9 ± 2.54e[c]
	25°C/50% rh; 30 min	65.0 ± 0.04c–e
	45°C/40% rh; 10 min	63.7 ± 0.94e
	45°C/40% rh; 30 min	63.7 ± 0.47e
	65°C/20% rh; 10 min	61.5 ± 0.28f
	65°C/20% rh; 30 min	43.1 ± 0.66h
Francis	25°C/50% rh; 10 min	64.6 ± 0.61de
	25°C/50% rh; 30 min	63.8 ± 0.14e
	45°C/40% rh; 10 min	63.7 ± 0.09e
	45°C/40% rh; 30 min	63.9 ± 0.47e
	65°C/20% rh; 10 min	62.0 ± 0.14f
	65°C/20% rh; 30 min	57.1 ± 0.47g
Wells	25°C/50% rh; 10 min	63.8 ± 0.09e
	25°C/50% rh; 30 min	65.0 ± 0.84c–e
	45°C/40% rh; 10 min	64.5 ± 1.46de
	45°C/40% rh; 30 min	65.2 ± 0.51c–e
	65°C/20% rh; 10 min	61.7 ± 0.18f
	65°C/20% rh; 30 min	40.8 ± 1.27i
Cypress	25°C/50% rh; 10 min	67.9 ± 0.09a
	25°C/50% rh; 30 min	67.7 ± 0.37a
	45°C/40% rh; 10 min	67.3 ± 0.47ab
	45°C/40% rh; 30 min	66.3 ± 0.18a–c
	65°C/20% rh; 10 min	65.9 ± 0.28b–d
	65°C/20% rh; 30 min	56.7 ± 0.75g

[a] Data are expressed as means ± standard deviations of three measurements.
[b] Temperature/relative humidity of the drying air; drying duration.
[c] Values followed by the same letters in the same column are not significantly different ($P < 0.05$).

Surface Lipid Content of Head and Broken Rice

The surface lipid contents (% rice) of head and broken kernels of rice cultivars from different drying treatments are presented in Table III. The surface lipid contents of the broken kernels were significantly greater than those of the head rice for all the rice cultivars and for all drying treatments. The surface lipid content of the milled rice depends on the residual bran present after milling. Because bran is the main source of lipid on milled rice, the surface lipid content of head and broken kernels showed that the broken kernels were undermilled relative to the head rice. This indicated that in McGill laboratory mills, the broken fractions were milled less than the whole kernel fractions.

The surface lipid contents of both head and broken rice produced by severe drying treatments were low relative to the head and broken rice produced by mild drying conditions. It showed that more surface bran was removed from rough rice exposed to severe drying condition relative to rough rice exposed to mild or moderate drying conditions. The rapid rate of rough rice moisture migration during severe drying relative to mild or moderate drying conditions may have contributed to the greater bran removal during milling. According to Chen et al (1998, 1999), the surface lipid content of a milled rice population depends on the relative number of thick and thin kernels. Chen and Siebenmorgen (1997) observed that for a given degree of milling, surface lipid content decreased with increasing milled rice kernel thickness. They also observed that more surface bran was removed from thick kernels than from thin kernels. The thin kernels are more susceptible to breakage and break first by mild and moderate drying, but as the drying condition change from mild and moderate to severe, thick kernels

TABLE III
Surface Lipid Content (%) of Head Rice and Broken Rice of Different Rice Cultivars Produced by Milling After Various Drying Treatments[a]

Rice Cultivar	Drying Treatment[b]	Head Rice	Broken Rice
Bengal	25°C/50% rh, 10 min	0.64 ± 0.01aB[c]	1.02 ± 0.04d–fA
	25°C/50% rh, 30 min	0.60 ± 0.00abB	1.02 ± 0.13d–gA
	45°C/40% rh, 10 min	0.58 ± 0.00bcB	1.03 ± 0.05d–fA
	45°C/40% rh, 30 min	0.59 ± 0.01abB	1.06 ± 0.01c–eA
	65°C/20% rh, 10 min	0.56 ± 0.02b–dB	1.00 ± 0.07e–iA
	65°C/20% rh, 30 min	0.56 ± 0.02b–eB	1.00 ± 0.11e–hA
Francis	25°C/50% rh, 10 min	0.53 ± 0.02c–gB	1.20 ± 0.02aA
	25°C/50% rh, 30 min	0.52 ± 0.02d–hB	1.17 ± 0.01abA
	45°C/40% rh, 10 min	0.50 ± 0.00e–iB	1.13 ± 0.01a–cA
	45°C/40% rh, 30 min	0.51 ± 0.00d–hB	1.11 ± 0.03a–dA
	65°C/20% rh, 10 min	0.45 ± 0.01i–mB	1.04 ± 0.06c–fA
	65°C/20% rh, 30 min	0.41 ± 0.01mB	1.07 ± 0.02b–eA
Wells	25°C/50% rh, 10 min	0.55 ± 0.00b–fB	1.01 ± 0.00d–hA
	25°C/50% rh, 30 min	0.52 ± 0.05d–hB	1.00 ± 0.00e–iA
	45°C/40% rh, 10 min	0.51 ± 0.06d–hB	1.04 ± 0.00c–fA
	45°C/40% rh, 30 min	0.52 ± 0.00c–hB	1.06 ± 0.02c–eA
	65°C/20% rh, 10 min	0.48 ± 0.07g–kB	1.02 ± 0.06d–gA
	65°C/20% rh, 30 min	0.43 ± 0.01k–mB	0.92 ± 0.00h–jA
Cypress	25°C/50% rh, 10 min	0.55 ± 0.01b–fB	0.98 ± 0.02e–jA
	25°C/50% rh, 30 min	0.50 ± 0.00f–iB	0.96 ± 0.01f–jA
	45°C/40% rh, 10 min	0.49 ± 0.03g–jB	0.90 ± 0.01ijA
	45°C/40% rh, 30 min	0.47 ± 0.03h–lB	0.89 ± 0.02jA
	65°C/20% rh, 10 min	0.44 ± 0.01j–mB	0.92 ± 0.02h–jA
	65°C/20% rh, 30 min	0.42 ± 0.01lmB	0.92 ± 0.03g–jA

[a] Data are expressed as means ± standard deviations; three surface lipid content measurements for each replicate; results are means of nine measurements.
[b] Temperature/relative humidity of the drying air; drying duration.
[c] Values followed by the same lowercase letters in the same column and the same uppercase letters in the same row are not significantly different ($P < 0.05$).

begin to break and change the ratio of thick and thin kernels in the head and broken rice population.

The low surface lipid content in broken rice produced by severe drying conditions is probably due to a greater proportion of thicker kernels in broken rice as produced by severe drying relative to mild drying.

Bengal head rice had significantly greater surface lipid content relative to the head rice of the other rice cultivars studied. This was probably due to the larger surface area to mass ratio for Bengal, relative to the other rice cultivars. Bengal is a medium grain cultivar that probably did not reach the equivalent residual bran contents as the long-grain cultivars in the 30-sec milling duration. It is also possible that Bengal had higher lipid content than other cultivars and hence produced milled rice with relatively higher surface lipid than the milled rice of other cultivars in equivalent milling duration.

TABLE IV
Surface Free Fatty Acids (FFA) Content of Head Rice and Broken Rice of Different Rice Cultivars Produced by Milling After Various Drying Treatments

Rice Cultivar	Drying Treatment[b]	Head Rice (%)	Broken Rice (%)
Bengal	25°C/50% rh, 10 min	0.035 ± 0.008a–eB[c]	0.061 ± 0.003a–dA
	25°C/50% rh, 30 min	0.036 ± 0.004a–dB	0.060 ± 0.002a–eA
	45°C/40% rh, 10 min	0.038 ± 0.006abB	0.064 ± 0.006abA
	45°C/40% rh, 30 min	0.040 ± 0.004aB	0.065 ± 0.002aA
	65°C/20% rh, 10 min	0.036 ± 0.004a–cB	0.062 ± 0.004a–cA
	65°C/20% rh, 30 min	0.035 ± 0.004a–eB	0.061 ± 0.005a–dA
Francis	25°C/50% rh, 10 min	0.033 ± 0.004a–fB	0.061 ± 0.005a–dA
	25°C/50% rh, 30 min	0.028 ± 0.003efB	0.060 ± 0.008a–eA
	45°C/40% rh, 10 min	0.027 ± 0.002fB	0.063 ± 0.013a–cA
	45°C/40% rh, 30 min	0.031 ± 0.004b–fB	0.064 ± 0.004abA
	65°C/20% rh, 10 min	0.032 ± 0.004b–fB	0.060 ± 0.009a–eA
	65°C/20% rh, 30 min	0.029 ± 0.004c–fB	0.057 ± 0.003a–eA
Wells	25°C/50% rh, 10 min	0.037 ± 0.001abB	0.055 ± 0.004a–eA
	25°C/50% rh, 30 min	0.033 ± 0.002a–fB	0.056 ± 0.004a–eA
	45°C/40% rh, 10 min	0.033 ± 0.004a–fB	0.061 ± 0.009a–dA
	45°C/40% rh, 30 min	0.029 ± 0.002c–fB	0.054 ± 0.002c–fA
	65°C/20% rh, 10 min	0.029 ± 0.003c–fB	0.059 ± 0.009a–eA
	65°C/20% rh, 30 min	0.033 ± 0.002a–fB	0.051 ± 0.004d–fA
Cypress	25°C/50% rh, 10 min	0.035 ± 0.005a–eB	0.051 ± 0.002efA
	25°C/50% rh, 30 min	0.033 ± 0.002a–fB	0.054 ± 0.002c–fA
	45°C/40% rh, 10 min	0.029 ± 0.008d–fB	0.054 ± 0.002b–fA
	45°C/40% rh, 30 min	0.030 ± 0.002c–fB	0.052 ± 0.004d–fA
	65°C/20% rh, 10 min	0.033 ± 0.001a–fB	0.051 ± 0.002efA
	65°C/20% rh, 30 min	0.029 ± 0.001c–fB	0.045 ± 0.001fA

[a] Data are expressed as means ± standard deviations; three surface FFA content measurements for each replicate; results are means of nine measurements.
[b] Temperature/relative humidity of the drying air; drying duration.
[c] Values followed by the same lowercase letters in the same column and the same uppercase letters in the same row are not significantly different ($P < 0.05$).

TABLE V
Hunter *b* Values of Head Rice and Broken Rice of Different Rice Cultivars Produced by Milling After Various Drying Treatments[a]

Rice Cultivar	Drying Treatment[b]	Head Rice	Broken Rice
Bengal	25°C/50% rh, 10 min	26.0 ± 0.99aB[c]	29.8 ± 0.03aA
	25°C/50% rh, 30 min	25.7 ± 0.19abB	29.2 ± 0.71aA
	45°C/40% rh, 10 min	24.7 ± 0.43bcB	29.4 ± 1.10aA
	45°C/40% rh, 30 min	24.8 ± 0.72bcB	29.8 ± 0.32aA
	65°C/20% rh, 10 min	24.1 ± 0.77cB	29.3 ± 0.81aA
	65°C/20% rh, 30 min	24.3 ± 1.23cB	29.2 ± 0.38aA
Francis	25°C/50% rh, 10 min	17.3 ± 0.30e–gB	20.9 ± 0.24bA
	25°C/50% rh, 30 min	17.2 ± 0.52e–gB	20.7 ± 0.19bA
	45°C/40% rh, 10 min	16.6 ± 0.62f–iB	20.4 ± 0.32bA
	45°C/40% rh, 30 min	16.8 ± 0.62e–hB	20.2 ± 1.06bA
	65°C/20% rh, 10 min	16.2 ± 0.39f–iB	20.0 ± 0.17bA
	65°C/20% rh, 30 min	16.2 ± 0.09g–iB	20.1 ± 0.75bA
Wells	25°C/50% rh, 10 min	18.0 ± 0.87dB	20.8 ± 0.98bA
	25°C/50% rh, 30 min	17.8 ± 1.43eB	20.4 ± 0.47bA
	45°C/40% rh, 10 min	17.1 ± 1.34e–gB	20.4 ± 0.29bA
	45°C/40% rh, 30 min	17.3 ± 1.03efB	20.5 ± 1.66bA
	65°C/20% rh, 10 min	16.4 ± 0.16f–hB	20.2 ± 0.80bA
	65°C/20% rh, 30 min	16.2 ± 0.10f–iB	20.0 ± 0.59bA
Cypress	25°C/50% rh, 10 min	16.5 ± 0.18fghB	20.9 ± 0.54bA
	25°C/50% rh, 30 min	16.2 ± 0.32fg–iB	20.8 ± 0.73bA
	45°C/40% rh, 10 min	15.9 ± 0.19hiB	20.6 ± 0.30bA
	45°C/40% rh, 30 min	15.9 ± 0.57hiB	20.1 ± 0.29bA
	65°C/20% rh, 10 min	15.6 ± 0.49iB	20.0 ± 0.92bA
	65°C/20% rh, 30 min	15.7 ± 0.43iB	20.0 ± 0.04bA

[a] Data are expressed as means ± standard deviations; three measurements for each replicate; results are means of nine measurements.
[b] Temperature/relative humidity of the drying air; drying duration.
[c] Values followed by the same lowercase letters in the same column and the same uppercase letters in the same row are not significantly different ($P < 0.05$).

Surface FFA Content of Head and Broken Rice

The surface FFA contents of head and broken kernels of rice cultivars from different drying treatments are presented in Table IV. The surface FFA contents of head rice for all rice cultivars dried under different drying conditions were within 0.027–0.040%. Broken kernels had significantly greater FFA levels than head rice. The surface FFA contents of broken kernels were within 0.045–0.065%. The major factor for FFA development on milled rice is the rate of lipid hydrolysis, which depends on the amount of surface lipids (substrate) and lipases (enzymes) (Tanako 1989). The surface FFA content of head and broken rice reflected the differences in surface lipid content between the head and broken rice for the long grain cultivars, showing that the surface lipid contents were the most significant factor for FFA development on long grain milled rice. FFA contents of Bengal (medium grain) were similar to that of the other cultivars, although the surface lipid content was greater than that of other cultivars. This was probably due to relatively slower hydrolysis in Bengal than in other long grain cultivars.

Hunter *b* Color Values of Head and Broken Rice

The Hunter *b* values of head rice and broken kernels as produced by different drying treatments are presented in Table V. Broken kernels had significantly greater *b* values relative to the head rice. The Hunter *b* values for both head and broken rice produced by severe drying conditions were low relative to the head and broken rice produced by mild drying conditions. Hunter *b* values of head and broken rice reflected the differences in surface lipid content between the severe and mild drying treatments. High *b* value from the large amount of residual bran on broken kernels indicated that they were undermilled. The Hunter *b* values of the head rice samples varied significantly across rice cultivars. Bengal was significantly more yellow than Francis, Wells, and Cypress.

CONCLUSIONS

The results of this study suggest that both drying and milling treatments have significant interactive effects on the surface lipid and FFA content of head and broken rice. Broken rice had significantly greater surface lipid content than head rice, which was due to the brokens being undermilled relative to the head rice. The surface FFA content of head and broken rice reflected the differences in surface lipid content between the head and broken rice and thus showed that the surface lipid content was the most significant contributing factor for FFA development on milled rice. This probably explains why broken rice is associated with greater FFA and off-flavor development in beer. Further milling of the brokens may solve the problem but will also reduce the milled rice yield. This extra step will also incur high cost in rice processing. The development of a milling machine with uniform bran removal efficiency, regardless of the size and thickness of the rice kernels, will allow brokens to be used by the brewing industry and improve the economic value of milled rice.

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