Effects of Nighttime Temperature During Kernel Development on Rice Physicochemical Properties

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ABSTRACT

Rice quality can vary inexplicably from one lot to another and from year to year. One cause could be the variable temperatures experienced during the nighttime hours of rice kernel development. During the fall of 2004, a controlled temperature study was conducted using large growth chambers, testing nighttime temperatures of 18, 22, 26, and 30°C from 12 a.m. until 5 a.m. throughout kernel development, using rice cultivars Cypress, LaGrue, XP710, XL8, M204, and Bengal. As nighttime temperature increased, head rice yields (HRY) significantly decreased for all cultivars except Cypress and Bengal, for which HRY did not vary among nighttime temperature treatments. Kernel mass did not vary among temperature treatments for any cultivar. Grain dimensions generally decreased as nighttime temperature increased. The number of chalky kernels increased with an increase in nighttime temperature for all cultivars but Cypress. The amylose content of Cypress and LaGrue was significantly lower at the nighttime temperature of 30°C, while total brown rice lipid and protein contents did not vary among temperature treatments for all cultivars.

Rice is primarily consumed as an intact kernel and therefore production quality is largely measured by head rice yields (HRY), which is the mass percentage of rough rice kernels that remain as head rice (kernels that are ≥75% of a whole, milled kernel (USDA 2005). Broken rice is worth only 50–60% of the value of head rice, meaning that a reduction in HRY can have severe economic repercussions for rice producers. Therefore, maximizing HRY is a major concern. Producers can influence HRY by optimally choosing harvest dates to avoid kernel fissure formation due to rapid moisture adsorption in the field (Kunze 1977). Improper drying and storage procedures can also cause kernel fissuring that can reduce HRY (Daniels et al 1998).

While HRY is determined in part by production practices, HRY can vary inexplicably from year to year and often from field to field, making it difficult for producers to predict yearly income and for processors to maintain a consistent end product. Moreover, in a given year, HRY can be uniform in one cultivar of rice and yet variable in another cultivar, leading to the suspicion that some cultivars are more resistant to quality variation. To achieve uniformity in the quality characteristics of rice, it is first necessary to have a clear understanding of the causes of these quality variations.

Rice quality can be influenced by genetics and environmental conditions such as ambient temperature during rice plant development (Webb et al 1979). While rice genetics can be altered through breeding programs, environmental temperatures are difficult to predict and can only be manipulated to some extent with the choice of planting dates. Environmental temperature during kernel development may play an integral role in causing the observed, unexplained fluctuations in rice grain quality (Cooper et al 2006).

Historical analyses have indicated that decreased yields were correlated with increased nighttime temperature during the growing season (Downey and Wells 1975; Peng et al 2004). Other historical analyses have correlated high nighttime temperatures during kernel development with decreases in HRY (Cooper et al 2006). High nighttime temperatures have been related to decreased panicle mass (Ziska and Manalo 1996) and an increase in the number of chalky kernels (Yoshida and Hara 1977). Yoshida and Hara (1977) noted that kernel dimensions decreased with increased nighttime temperature. Sun and Siebenmorgen (1993) and Siebenmorgen (2006) showed that HRY is influenced by the thickness distribution pattern of a population of rice kernels. By altering the thickness distribution of kernels, an increase in nighttime temperature could potentially reduce HRY.

In a japonica cultivar, high nighttime temperatures during kernel development caused an increase in amylose content (Resurreccion et al 1977). Counce et al (2005) observed that as nighttime temperature increased, HRY decreased, while the proportion of long chains of amylopectin decreased. This suggests that HRY could be related to the cellular structure of the starch-containing molecules within rice kernels and that this structure, and thus HRY, could be temperature-sensitive.

A controlled temperature study was conducted to better understand the causes of HRY and processing quality variations. The objective was to quantify the effects of nighttime temperature during kernel development on rice physical and chemical properties.

MATERIALS AND METHODS

Cultivars and Treatments

One hundred and ninety-two plants of each of six rice cultivars, chosen based on observed milling characteristics (Table I), were grown in a greenhouse until the grain-filling stage of kernel development, or when one kernel on the plant mainstem filled to the end of its caryopsis with starch (stage R5 according to Counce et al [2000]). Once this developmental stage was reached, 48 plants of each cultivar were transferred into one of four phytotrons (large growth chambers). Each phytotron contained four beds, each measuring 0.84 m (W) × 2.36 m (L) × 0.38 m (D). Six experimental units were placed in each of the four beds; each experimental unit comprised 12 plants of one cultivar.

The daytime temperature profile was identical in all four phytotrons but the temperatures between 12 p.m. and 5 a.m. were controlled at 18, 22, 26, or 30°C, comprising the experimental treatments of this study. The daytime (5 a.m. until 12 p.m.) temperature profile within the phytotrons was determined through an analysis of historical daily weather data from six locations located in the rice-growing regions of the southern United States. Figure 1 demonstrates the actual temperatures within each phytotron.

Harvest and Analysis

Once the rice kernels had reached 17–20% moisture content (MC), determined as the average MC of 50 kernels using an individual kernel moisture meter (CTR-800E, Shizuoka Seiki, Shizuoka, Japan), rice panicles were hand-harvested and threshed with

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a single-panicle thresher (Hege-Maschinenbrau D7112, Hans-Ulrich, Germany). After harvest, rice samples were dried to 12% MC on screened trays in a chamber maintained at 23°C and 57% rh by a temperature and rh control unit (Climate Lab AA, Parameter Generation & Control, Black Mountain, NC). Chaff and empty hulls were removed from the dried rice samples using an aspirator (grain blower, Seedburo Equipment, Chicago, IL). Samples were stored in locking plastic bags at 4°C before physical and chemical tests. To obtain enough rough rice to complete all physical and chemical tests, the rice of each cultivar from experimental units in the two blocks (beds) at the front of each phytotron and the two blocks at the back of each phytotron were pooled. Pooled blocks were subsequently analyzed as replicates.

Physical Tests

Rough rice samples were milled for 30 sec in a 35-g capacity laboratory rice mill (modified #2 McGill mill, Rapsco, Brookshire, TX) with a 2.04-kg load on the mill chamber. Due to the limited amount of sample, only 30 g of the medium-grain cultivars Bengal and M204 were milled, while 35 g of the long-grain and the hybrid cultivars were milled. Tests (data not shown) determined that milling rough rice in 35 g and 30 g amounts using the modified laboratory rice mill produced samples of comparable HRY (60.4% and 60.0%, respectively) and degree of milling (DOM) (surface lipid contents [SLC] of 0.24% and 0.23%, respectively). Once milled, the samples were aspirated (Seedburo grain blower) for 30 sec to remove loose particles of bran. HRY was measured using an image analysis system (2312 Grain Check, Foss North America, Eden Prairie, MN). Head rice was then separated from broken kernels using a Seedburo sizing device.

Degree of milling, as SLC, was determined using a lipid extraction system (Soxtec Avanti 2055, Foss North America) following the procedure of Matsler and Siebenmorgen (2005) with modifications in sample size (3 g of head rice instead of 5 g) due to the limited amount of sample. In brief, 3 g of head rice was weighed into cellulose thimbles (Foss North America); the thimbles and head rice were predried for 1 hr in an oven maintained at 100°C. Subsequently, lipid was extracted from the sample utilizing 70 mL of petroleum ether (boiling point 35–60°C; VWR, Suwanee, GA). The hot plate below the extraction cups was heated to 135°C while the thimbles were immersed in the extraction cup solvent for a boiling duration of 20 min, then raised above the solvent and rinsed with petroleum ether condensate for 30 min. After rinsing, the extraction cups were removed from the Soxtec unit and placed into an oven maintained at 100°C for 30 min to allow evaporation of the solvent. Samples were then placed in a desiccator at room temperature for ≈30 min to cool before being weighed. The difference between the mass of the cups containing the extracted lipid and the original empty cup mass was then calculated to obtain the mass of the extracted lipid. SLC was expressed as the mass percentage of extracted lipid mass to the original head rice sample mass.

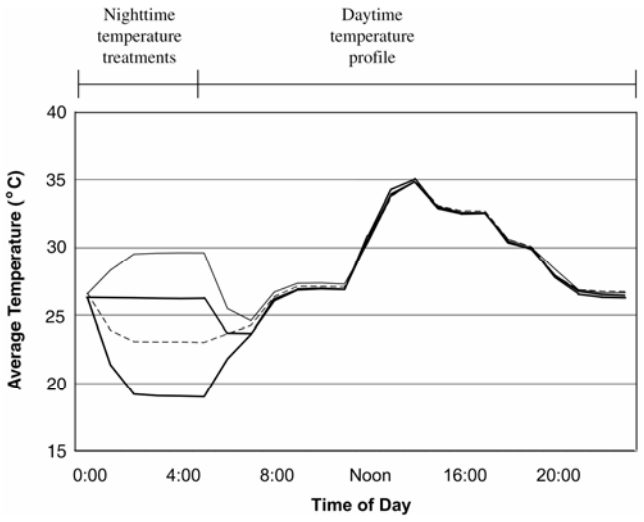

Fig. 1. Measured temperature profiles within the phytotrons. Each profile was obtained by averaging, at 2-hr intervals, the actual air temperature from two canopy-height temperature sensors over the study duration.

Previous studies (Reid et al 1998, Cooper and Siebenmorgen 2006) have found that DOM and HRY are linearly correlated. HRYs were adjusted for differing SLCs based on the method of Cooper and Siebenmorgen (2006), using Equation 1.

$$HRY_{adjusted} = HRY_{sample} - 9.4\,(SLC_{sample} - SLC_{standard}) \quad 1$$

where $HRY_{adjusted}$ = the HRY of a rice lot, adjusted for differences in SLC between the sample SLC and the desired, specified SLC (%); HRY_{sample} = the HRY of a sample with a given DOM (SLC_{sample}) (%); SLC_{sample} = the SLC of a sample, (%); $SLC_{standard}$ = the predetermined, specified SLC of a standard or processing application (%).

This method maintains that HRY changes by 9.4 percentage points (pp) for every pp change of SLC. In the current study, the chosen $SLC_{standard}$ was 0.5 %.

The grain mass of 200 rough rice kernels of each cultivar/temperature treatment replicate was determined using an analytical balance. Each rough rice kernel was then manually shelled and the length, width, and thickness of the resultant brown rice kernel were determined using an image analyzer (RIA, Satake Corporation, Hiroshima, Japan). The brown rice used in the dimensional analyses was sealed in plastic bags until use in the breaking force analyses, conducted using a texture analyzer (TA-XT2i Texture Analyzer, Texture Technologies Corporation, Scarsdale, NY). Brown rice kernels (200) of each cultivar/temperature replicate were individually loaded onto a supporting apparatus with a distance of 3.4 mm between the supporting points; the deformation rate was set at 0.5 mm/sec. The loading head had a flat end with a thickness of 1.5 mm and a width of 9.9 mm. Breaking force was taken as the maximum force required to break a single kernel of brown rice.

Chalkiness was determined through visual examination of duplicate 15-g portions of head rice (≈750 kernels) of each cultivar/temperature treatment replicate (Patindol and Wang 2003). Rice kernels with opaque regions totaling ≥50% of the kernel were classified as chalky (USDA 2005). Chalky kernels were then weighed and chalkiness expressed as the mass percentage of chalky kernels to the total, 15 g mass of head rice.

TABLE I
Cultivars and Hybrids Evaluated in Nighttime Temperature Evaluation Study Chosen Based on Observed Milling Characteristics

Cultivar	Rice Type	Observed Characteristics (prestudy)
Cypress	Long-grain cultivar	Consistent milling quality
LaGrue	Long-grain cultivar	Variable milling quality
M204	Medium-grain cultivar	Commonly cultivated in western U.S., predictable milling quality
Bengal	Medium-grain cultivar	Commonly cultivated in southern U.S., variable milling quality
XP710	Long-grain hybrid	Unestablished milling quality
XL8	Long-grain hybrid	Good milling quality

Chemical Analyses

All chemical analyses were conducted using brown (total lipid and protein content) or head rice (amylose content, amylopectin chain length distribution, and flour viscosity properties) that was ground into flour using a laboratory mill (cyclone sample mill, Udy Corporation, Fort Collins, CO) equipped with a 0.5-mm screen. The MC of the flour was determined by drying 1 g of head rice flour at 135°C for 1 hr, which was then cooled in a desiccator and weighed. Moisture content was expressed as a mass percentage of the original 1 g mass of flour.

The total lipid content was determined using 3 g of brown rice flour with the lipid extraction system and method as described previously for SLC determination.

The total nitrogen content of 0.05 g of brown rice flour was determined using a combustion method according to Approved Method 46-30 (AACC International 2000) with a nitrogen analyzer (Fisons NA-2000, Rhone-Poulenc Rorer, Collegevale, PA). Total nitrogen was expressed as % protein, assuming that rice protein is composed of 16.8% nitrogen.

Apparent amylose content was determined using the colorimetric method described by Juliano (1971), with absorbance measured at 620 nm using a spectrophotometer (DU520, Beckman Coulter, Fullerton, CA). The amount of amylose in the sample was determined through interpolation of a standard curve, which was prepared with potato amylose and waxy rice starch, also described by Juliano (1971) and expressed as a dry basis percentage.

Starch was isolated from 2 g of head rice flour using the alkali-steeping method (Yang et al 1984). The isolated starch, mixed with a pH 3.5 buffer solution was then treated with 15 μL of isoamylase (glycogen 6-glucanohydrolase, Hyashibara Biochemical Laboratories, Japan), which hydrolyzed the α-1,6-glucosidic linkages of the amylopectin molecules at 40°C for 48 hr. Subsequently, chain-length distribution of amylopectin was determined by high-pressure anion-exchange chromatography with pulsed amperometric detection (DX500, Dionex Corporation, Sunnyvale, CA) as in Patindol and Wang (2003).

Pasting properties of head rice flour were measured with a Rapid Visco Analyzer (RVA-4 Series, Newport Scientific Pty, Ltd, Warriewood, NSW, Australia) according to Approved Method 61-02 (AACC International 2000). Rice flour (3.0 g) was weighed into an aluminum canister with ≈25 g of distilled water (more or less water was added if the flour MC was lesser or greater than 12% wb, respectively). After the sample was held at 50°C for 1.5 min, it was heated at a rate of 12°C/min to 95°C, held at 95°C for 2.0 min, and cooled at a rate of 12°C/min to 50°C.

Statistical Analysis

Data were analyzed with JMP software (6.0, SAS Institute, Cary, NC). Student's *t*-tests were used to compute differences between means at $P < 0.05$. Statistical differences were computed within each cultivar group only.

RESULTS AND DISCUSSION

Although the rice samples were milled for the same duration and in the same laboratory mill, the DOM was not consistent. Surface lipid content was 0.20–0.38% for Cypress, 0.18–0.25% for LaGrue, 0.34–0.70% for Bengal, 0.42–0.57% for M204, 0.23–0.48% for XL8, and 0.26–0.46% for XP710. As such, the HRY values were adjusted for the SLC of the samples according to Equation 1 to equitably compare the HRY among temperature treatments within each cultivar. Figure 1 shows the HRY results from the milling and adjustment analyses.

The milling procedure yielded some $HRY_{adjusted}$ values that were >70%, values that are rarely observed in commercial milling. However, the rice produced through this experiment had been harvested, threshed, and dried using the most gentle means possible to isolate the effects of nighttime temperature and to exclude any HRY differences due to processing techniques, resulting in high HRY.

The $HRY_{adjusted}$ of rice hybrids XL8 and XP710 decreased as nighttime temperature increased. Differences of 23 percentage points (pp) and 7 pp were observed in the $HRY_{adjusted}$ values of XL8 and XP710, respectively, grown at 18 and at 30°C nighttime temperatures. The long-grain cultivars reacted to changes in nighttime temperature as predicted by the reputed milling quality (Table I). Cypress, which is generally known as a consistently stable milling cultivar, showed a decrease in $HRY_{adjusted}$ only at 26°C, but was otherwise stable across the other tested tempera-

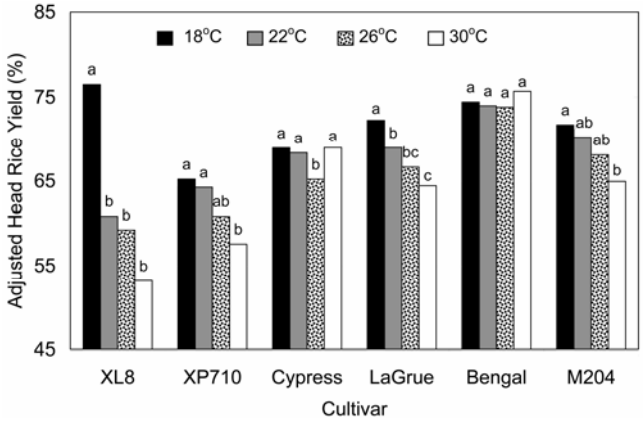

Fig. 2. Head rice yields of indicated cultivars, adjusted for degree of milling using Eq. 1. Surface lipid content of 0.5% was used as a basis of comparison to calculate adjusted head rice yields. Means within each cultivar group with the same letter were not significantly ($P > 0.05$) different.

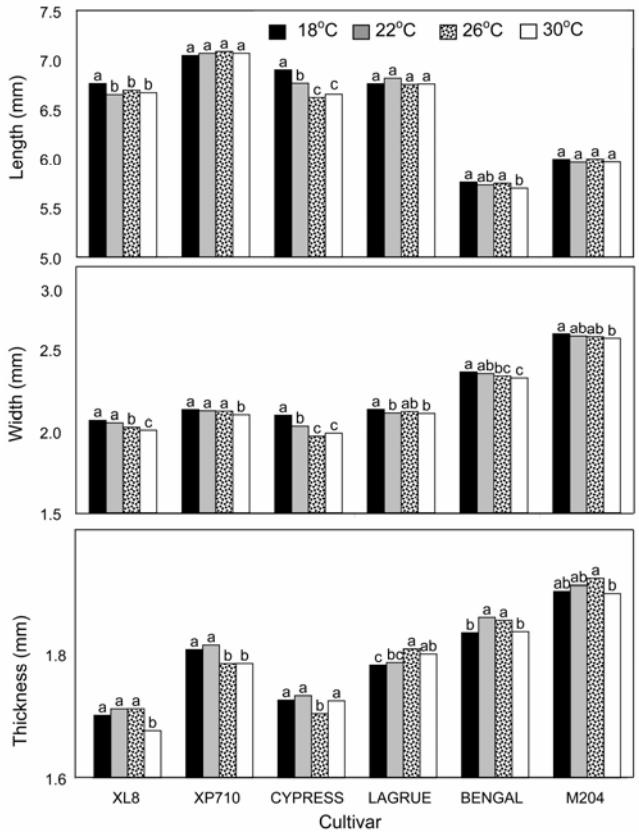

Fig. 3. Average brown rice kernel length, width, and thickness of indicated cultivars grown at 18, 22, 26, and 30°C nighttime air temperatures (two replicates of 200 brown rice kernels). Means within each cultivar group with the same letter were not significantly ($P > 0.05$) different.

tures. For LaGrue, a cultivar which is generally known to have variable milling characteristics, $HRY_{adjusted}$ decreased steadily with increased nighttime temperature. The medium-grain cultivars did not react to the temperature treatments as expected from observed milling quality. Though Bengal reportedly had variable milling quality, Bengal $HRY_{adjusted}$ was consistent across all nighttime temperatures. In fact, Bengal $HRY_{adjusted}$ were very high, exceeding 74% across all temperature treatments. Conversely, cultivar M204 is generally known for its predictable processing quality and yet its $HRY_{adjusted}$ steadily decreased as nighttime temperature increased. M204 is predominantly grown in California, where the climate exhibits little temperature variability during the rice-growing season. Therefore, it is possible that this response to higher nighttime temperature was not previously observed, as its usual growing temperature does not vary much.

Studies have shown that as daytime and mean daily temperature increased, grain mass decreased (Sato and Takahashi 1971; Yoshida and Hara 1977). However, Yoshida and Hara (1977) noted that grain mass did not vary significantly with changes in nighttime temperature for a japonica and an indica rice cultivar. Similarly, in this study, the rough rice 200-kernel mass did not significantly change in response to nighttime temperature variation for any cultivar or hybrid. The average rough rice 200-kernel mass values for each cultivar were 4.2, 4.5, 4.3, 4.1, 5.1 and 4.5 g for XL8, XP710, LaGrue, Cypress, M204, and Bengal respectively.

Figure 3 shows the average brown rice kernel length, width, and thickness of the tested cultivars grown at the various nighttime temperatures. Of all dimensions, kernel length was the most stable in response to changes in nighttime temperature. Tashiro and Wardlaw (1991) also found that brown rice kernel length was

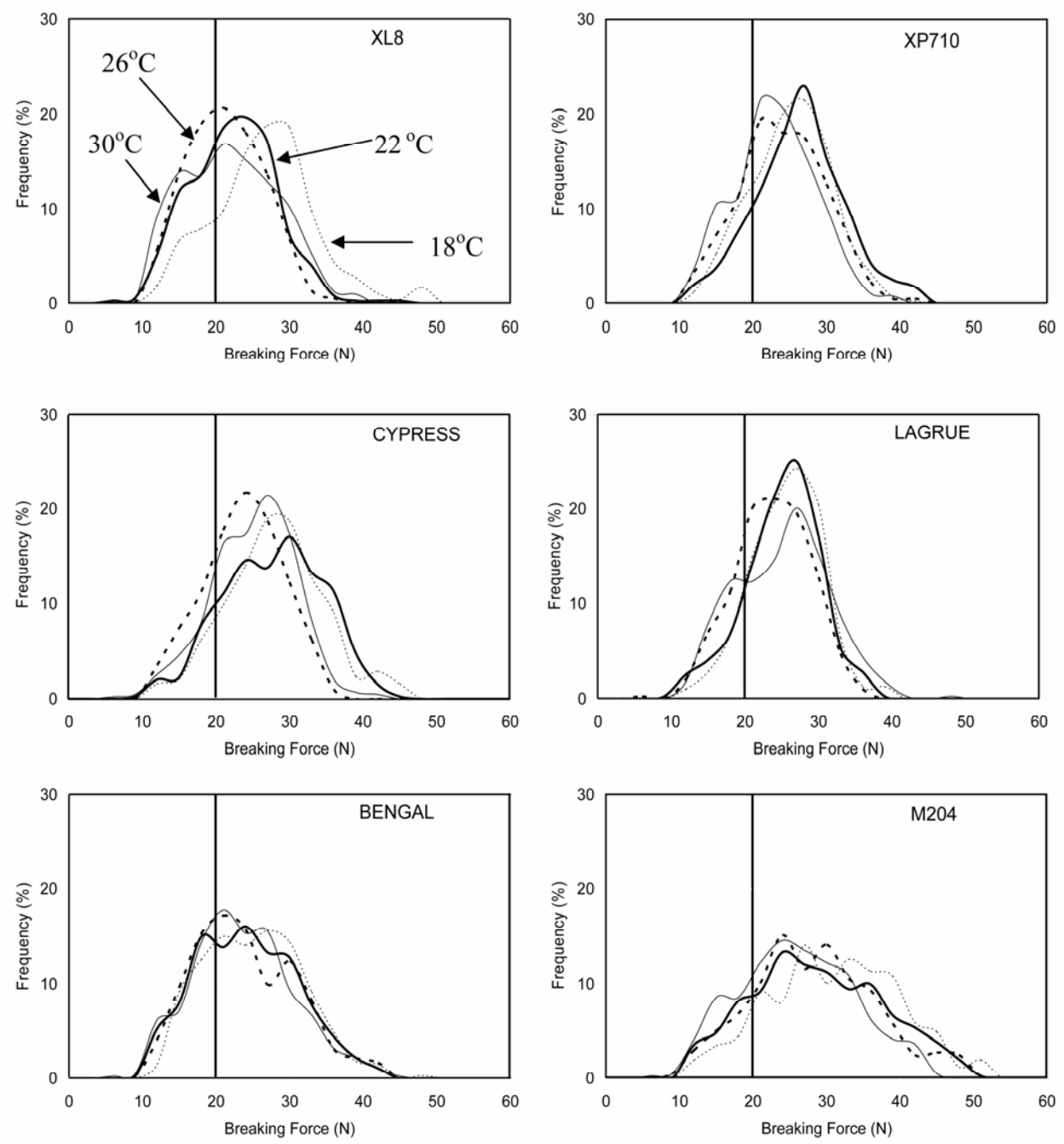

Fig. 4. Breaking force distributions of indicated cultivars grown at 18, 22, 26, and 30°C nighttime air temperatures determined through three-point bending tests (two replicates of 200 brown rice kernels). Brown rice kernels requiring a force >20 N to break were classified as "strong" kernels and correlated with adjusted head rice yield (Fig. 5).

the most stable of all dimensions in response to mean daily temperature changes. No significant difference in mean brown rice kernel length was found for cultivars XP710, LaGrue, and M204, and only slight, yet significant, differences were found for cultivars XL8 and Bengal. Cypress kernel length, however, significantly decreased from the 18°C nighttime temperature.

Increasing nighttime temperatures caused a decrease in brown rice kernel width for all tested hybrids and cultivars (Fig. 3). Counce et al (2005) found that Cypress and LaGrue kernel width significantly decreased when nighttime temperature increased from 18 to 24°C. However, Counce et al (2005) did not find a significant difference in kernel thickness. In this study, nighttime temperature did significantly affect kernel thickness, though not linearly. Kernel thickness tended to be maximized at a particular nighttime temperature, which varied with cultivar. For hybrid XL8, only the nighttime temperature at 30°C caused a significant decrease in kernel thickness, and for XP710 kernel thickness was significantly lower at 26 and 30°C than at 18 and 22°C (Fig. 3). Cypress thickness only decreased at 26°C. LaGrue kernels were thinnest when grown at 18°C nighttime temperature and thickest at 26°C. M204 kernels were also thickest at 26°C nighttime temperature. Bengal was thinner at 18 and 30°C than at 22 and 26°C. HRY values have been correlated with rice kernel thickness distributions (Lu and Siebenmorgen 1995; Siebenmorgen and Qin 2005; Siebenmorgen et al 2006). Interestingly, Cypress kernel thickness was significantly lower at 26°C compared with that at the other tested temperatures, which corresponded with a decrease in $HRY_{adjusted}$ at the same temperature. However, Cypress average thickness and $HRY_{adjusted}$ did not show significant correlation in an analysis of variance analysis, nor did Cypress width. The average width, thickness, and length of Cypress, LaGrue, Bengal, and M204 were not significantly correlated with $HRY_{adjusted}$, nor was there any dimensional interaction. The average width of XL8 and the average thickness of XP710 were significantly correlated ($P < 0.05$) with $HRY_{adjusted}$.

Figure 4 shows the breaking force distributions of each cultivar grown at the four tested nighttime temperatures. For the most part, the distributions were not normal but were multimodal, which was expected based on previous studies (Qin and Siebenmorgen 2005; Siebenmorgen and Qin 2005). For all cultivars, the rice grown at 18°C nighttime temperature tended to have more strong kernels (defined by Siebenmorgen and Qin (2005) as brown rice kernels requiring >20 N to break in a three-point bending test) than rice grown at other temperatures. Moreover, for all cultivars, rice grown at 30°C tended to have multimodal breaking force distributions, with an extra mode in the "weak kernel", < 20 N breaking force zone.

Siebenmorgen and Qin (2005) demonstrated that the percentage of strong kernels in a rice bulk was directly correlated with HRY. In concurrence, the $HRY_{adjusted}$ of all cultivars in the current study, excluding Bengal, was linearly correlated with the number of kernels requiring >20 N to break, with a R^2 of 0.54 (Fig. 5). Bengal rice had very high $HRY_{adjusted}$ values, and thus was not correlated with the percentage of strong kernels. These results are consistent with those of Qin and Siebenmorgen (2005), who found that some rice samples with consistently high HRY were not correlated with the number of strong kernels in a rice sample, though it was speculated that the choice of 20 N as the force level delineating weak from strong kernels could be different depending on cultivar. Lu and Siebenmorgen (1995) suggested that the delineating force separating weak from strong kernels could range between 14.5 and 16 N. The Bengal breaking force distribution (Fig. 4) was multimodal, but with one mode within the "weak kernel" zone. The force level separating the two modal populations was ≈15 N, indicating that this may be a better force level to delineate between strong and weak kernels for this cultivar. However, the percentage of kernels that required >15 N breaking force was also not correlated to Bengal HRY.

Chalkiness is an undesirable aesthetic and processing characteristic of rice that can be caused by the depression of cell growth and insufficient accumulation of starch (Nagato and Ebata 1965). This process causes the kernel amyloplasts to become loosely clustered as the rice kernel matures (Lisle et al 2000). Figure 6 shows the effect of nighttime temperature on the chalkiness of the tested cultivars. The chalkiness of hybrid XL8 increased significantly with nighttime temperature, from 23% at 18°C to 34% at 30°C. The chalkiness of XP710, LaGrue, and M204 also increased with increased nighttime temperature. There was no significant difference in the chalkiness of Cypress rice grown at any nighttime temperature. Bengal samples had 0.6–2.0% chalky kernels, the lowest amount of all tested cultivars. Bengal rice grown at 18°C was significantly less chalky than rice grown at 22°C nighttime temperature. Many previous studies have observed increased chalkiness with increased temperature regimes (Nagato and Ebata 1965; Nagato and Chaudhry 1969; Tashiro and Ebata 1975; Yali and Zhiguo 1997; Lisle et al 2000). Yoshida and Hara (1977) noted that chalkiness increased as nighttime temperature increased, except when nighttime temperature was very low (14°C), which also caused an increase in chalkiness.

Nighttime temperature did not have a significant effect on the amylose content of XL8, XP710, or M204 (Fig. 7). Bengal amy-

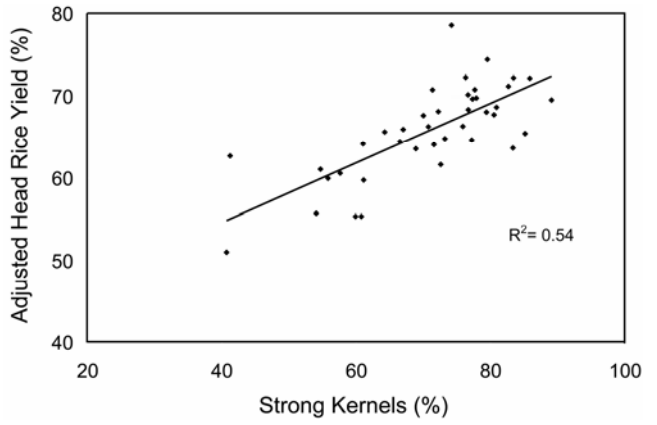

Fig. 5. Head rice yields (HRY), adjusted for surface lipid content, as affected by percentage of strong kernels in rice samples (Fig. 4). Strong kernels are those requiring >20 N of force to break in a three-point bending test on brown rice. Each data point represents percentage of strong kernels in each of two replicates of 200 brown rice kernels of each cultivar/temperature treatment. Bengal was excluded from the analysis as adjusted HRY values were consistently high across temperature treatments and were uncorrelated with percentage of strong kernels in the samples.

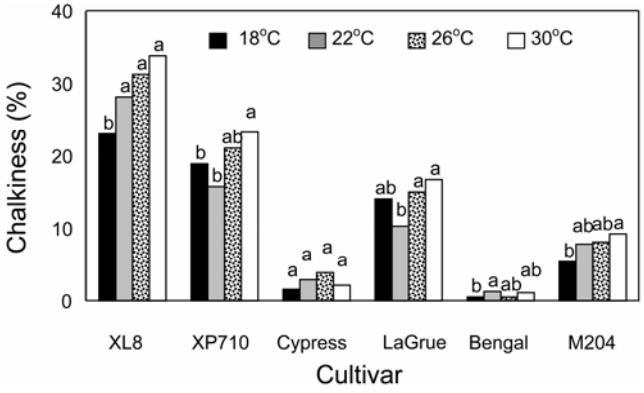

Fig. 6. Chalkiness of indicated cultivars grown at 18, 22, 26, and 30°C nighttime air temperatures expressed as the mass percentage of 15 g of head rice, performed in duplicate. Means within each cultivar group with the same letter were not significantly ($P > 0.05$) different.

lose content significantly decreased when nighttime temperature increased from 18 to 22°C, at which point amylose content remained static at further increases in nighttime temperature. The amylose content of both Cypress and LaGrue significantly decreased at the 30°C nighttime temperature. The effects of temperature on rice amylose content has long been observed and investigated. Ayres et al (1997) showed that variation in the amylose content of U.S. rice cultivars can be explained by the presence of a single-nucleotide polymorphism of AGGTATA to AGTTATA in the allele encoding for granule-bound starch synthase (GBSS), the enzyme that forms amylose. This polymorphism is temperature sensitive; those cultivars with the AGTTATA allele accumulate fewer mature GBSS transcripts at high temperatures (Larkin and Park 1999). However, Cypress and LaGrue both contain the non-temperature-sensitive allele AGGTATA (Ayres et al 1997). Therefore, the significant amylose decrease observed at 30°C in Cypress and LaGrue rice was most likely not caused by the genetically explained depression of GBSS production. Rather, a physiological functioning could be affected at high nighttime temperatures, such as a reduction in the GBSS enzymatic rate.

Nighttime temperature significantly affected the amylopectin chain length distribution of the long-grain cultivars but not any hybrid or medium-grain cultivar. As shown in Table II, at 22°C nighttime temperature, the proportion of Cypress amylopectin chains with degree of polymerization (DP) of 13–24 glucose units significantly increased. Moreover, at 30°C, the proportion of long chains of amylopectin (>DP37) of LaGrue significantly increased. Therefore, the long-grain cultivars did not react similarly to temperature treatment. These findings are contrary to those of Counce et al (2005), who noted that both Cypress and LaGrue showed increased proportions of long chains of amylopectin at 24°C nighttime temperature compared with 18°C nighttime temperature. Previous studies have shown that lower temperatures lead to an increased proportion of shorter amylopectin chains (DP6–13) and a decreased proportion of longer chains (DP>20) (Asaoka et al 1985; Umemoto et al 1999; Inouchi et al 2000; Suzuki et al 2002). However, Lisle et al (2000) did not find any differences in the amylopectin chain length distributions in three rice cultivars produced at different daily mean temperatures. It is possible that the effect of temperature on amylopectin chain lengths is varietal. However, results may have been confounded by effects of the alkali used during starch isolation, which reportedly caused damage to the fine structure of the starch (Chiou et al 2002). In the current study, no correlation between amylopectin chain lengths and milling quality was found.

Nighttime temperature did not affect rice pasting properties consistently across cultivars. Peak viscosity (PV) was unaffected by nighttime temperature for all cultivars except for Cypress, for which PV was significantly higher at 30°C (204.4 RVU) than at 18°C (188.8 RVU). Decreased nighttime temperature caused a significant decrease in final viscosity (FV) for XL8 (240.9 and 256.0 RVU at 18 and 30°C, respectively), but caused a significant increase in FV for Bengal (181.5 and 165.5 RVU at 18 and 30°C, respectively). Otherwise, pasting properties were not affected by nighttime temperature treatment.

The total protein content of any of the tested cultivars did not vary significantly in response to changes in nighttime temperature. Average brown rice protein contents of each cultivar across temperature treatments were 11.4, 11.8, 10.8, 10.8, 9.7, and 12.3% for XL8, XP710, Cypress, LaGrue, Bengal, and M204, respectively.

The total brown rice lipid content did not vary significantly with nighttime temperature for the long-grain or the medium-grain cultivars, although it significantly increased at the 30°C nighttime temperature for both XL8 and XP710. The average total lipid contents of each cultivar, across temperature treatments, were 2.3, 2.7, 2.8, 2.6, 2.5, and 2.8% for XL8, XP710, Cypress, LaGrue, Bengal, and M204, respectively.

CONCLUSIONS

Milling quality, adjusted for the DOM of the milled rice samples, decreased with increased nighttime temperature for both tested hybrids (XL8 and XP710), long-grain cultivar LaGrue, and medium-grain cultivar M204. The $HRY_{adjusted}$ of cultivar Bengal were not significantly affected by changes in nighttime temperature, whereas those of Cypress only decreased at the 26°C nighttime temperature. All $HRY_{adjusted}$ values, excluding those of Bengal, were correlated with the percentage of strong kernels in the samples, defined as brown rice kernels requiring >20 N to break in a three-point bending test.

Increased nighttime temperature caused brown rice kernel length to decrease for cultivars XL8, Cypress, and Bengal, and kernel width to decrease for all cultivars. Kernel thickness seemed to be maximized at 26°C for most cultivars. Chalkiness generally

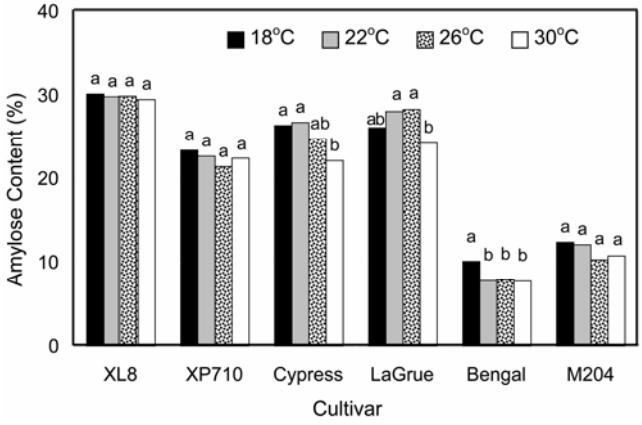

Fig. 7. Milled rice amylose content of indicated cultivars grown at 18, 22, 26, and 30°C nighttime air temperatures. Each data point represents the average of two replicates for which measurements were performed in duplicate. Means within each cultivar group with the same letter were not significantly ($P > 0.05$) different.

TABLE II
Amylopectin Chain-Length Distributions, Expressed as Degree of Polymerization (DP) of Two Long-Grain Cultivars as Affected by Nighttime Temperature[a]

Cultivar	Nighttime Temperature	DP6–12	DP13–24	DP25–36	DP37–65
Cypress	18°C	24.1a	52.3b	11.8a	11.8a
	22°C	23.7a	53.1a	12.2a	11.0a
	26°C	24.0a	52.4b	21.0a	11.7a
	30°C	23.7a	52.5ab	11.9a	12.0a
LaGrue	18°C	24.0a	53.3a	11.8a	11.0b
	22°C	23.8a	52.9a	11.8a	11.4ab
	26°C	24.1a	53.2a	12.1a	10.6b
	30 °C	23.3a	51.6a	12.4a	12.6a

[a] Means within each cultivar orDP group followed by the same letter were not significantly different ($P > 0.05$).

increased as nighttime temperature increased, but particularly for the hybrid cultivars.

The total brown rice lipid and protein content did not vary among temperature treatments for all cultivars. Nighttime temperature did not significantly affect the amylose content of XL8, XP710, or M204 cultivars. The amylose content of Cypress and LaGrue significantly decreased at the nighttime temperature of 30°C, while it decreased at 18°C for Bengal. Nighttime temperature did not have a significant effect on the amylopectin chain length distributions of the medium-grain and hybrid cultivars. For Cypress, there was a significant increase in the proportion of DP13–24 amylopectin chains at 22°C nighttime temperature, while at 30°C, the proportion of long-chains of amylopectin, DP>37 of LaGrue increased. Thus, long-grain cultivars did not react similarly to temperature treatment.

In summary, nighttime temperature treatments induced some small chemical property changes in the tested cultivars and hybrids and also affected dimensions and breaking force distributions to a certain extent. However, in the cultivars in which HRY was most dramatically affected by nighttime temperatures, chalkiness levels were also most profoundly influenced.

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