5 Assessing Rice Milling Quality

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5.1 Chapter Overview

Laboratory milling systems are used throughout the rice industry to

1) estimate the milling quality that may be expected of rice lots when milled in large-scale milling systems, and
2) produce milled rice from which visual, functional, sensory, and nutritional assessments of the rice lot can be made.

This chapter first details factors that impact the overall milling quality of rice, focusing primarily on production factors. Of particular note are the deleterious impacts of high nighttime air temperatures during kernel reproductive development on kernel chalkiness and resultant milling quality reductions. This discussion is timely, as the historically-high temperatures experienced in the Mid-South rice production region of the United States in 2010, and to a lesser degree 2011, are believed to be generally responsible for instances of poor-quality rice produced during that time frame. A discussion of individual kernel property distributions as a fundamental basis for explaining milling yield differences related to harvest moisture content follows. This section not only documents some of the reasons for milling yield variation, but also establishes that a rice bulk comprises kernels with inherently different physicochemical properties, which also explains some behavioral patterns during actual milling.

Most of the discussion of laboratory milling quality assessment centers on the McGill #2 rice mill, one of, if not the most popular laboratory-scale mills used in the United States. The factors that affect the performance of this mill are detailed, as are the factors of the rice that determine milling yield, the predominant of which is the physical integrity of the kernels. While the physical integrity of kernels is set prior to milling, the degree of milling, which is the degree to which bran is removed from kernels in the mill, also impacts milling yield and overall rice functional quality. The importance of the degree of milling, its impact on milling yields, and an approach of using the degree of milling to correct milling yields are discussed. Finally, the impacts that the degree of milling has on proximate composition, functionality, and cooking/textural properties of milled rice are provided.

5.2 Introduction

The term "rice quality" can have many different meanings from one culture to another, one country to another, and even one economic/processing segment of the rice industry to another. Rice quality assessment may include objective physical and chemical measurements, as well as more subjective visual judgments. Because of this, it can be challenging to assess the full-spectrum quality of a rice lot prior to full-scale processing, and yet it is usually necessary to do so for assigning trade and/or processing value to the lot. Because of the substantial economic and end-use implications associated with milling quality indices, this chapter is devoted to laboratory-scale assessment of milling quality, and the rice and milling system factors that impact this assessment.

Laboratory-scale milling systems have long been used to estimate the milling performance that can be expected of a rice lot when milled in large, industrial-scale systems. Laboratory systems comprise equipment that first removes the hull from the rough rice kernel, producing brown rice. There are some physicochemical properties of brown rice that are often of interest, particularly in research settings. However, unless the lot is being processed to produce brown rice, in which case the intact caryopsis is of interest, brown rice is typically milled to remove the germ and bran layers, leaving the starchy endosperm. The predominant measurements of rice milling yield are conducted using the endosperm, i.e. the milled rice fraction. Milled rice may also be analyzed to estimate functional or end-use processing performance. As indicated above, the degree to which the bran layers are removed from the caryopsis, the degree of milling, plays a significant role in determining overall milling yield/quality, as well as milled rice constituent properties and functionality.

Two of the primary measures of milling "quality" are milled rice yield and head rice yield. Milled rice is the component of rough rice produced by removing the hulls, germ, and most of the bran; milled rice includes intact and broken kernels. Milled rice yield is calculated as the mass fraction of rough rice remaining as milled rice. Broken kernels, defined by the United States Department of Agriculture (USDA) as those that are "less than three-fourths of whole kernels"[1], are typically removed from the milled rice stream. The remaining "whole" kernels are generally known in the milling industry as "head rice". Head rice yield is the mass fraction of rough rice that remains as head rice.

As expounded later in the chapter, both milled rice yield and head rice yield are highly dependent upon the physical integrity of the endosperm, as well as the extent to which bran and endosperm are removed during milling. In most markets, broken kernels are valued at only 50 to 60 % that of head rice, thus underpinning the tremendous impact that head rice yield has on the economic value of a rice lot, and also justifying the need for laboratory milling systems to accurately estimate this important parameter.

5.3 Factors Affecting Milling Quality

The physical condition or strength of the rice kernel is the most important determinant of milling yield. When kernels are fissured, or otherwise physically damaged, they are less likely to withstand the aggressive actions of dehulling and milling, resulting in a greater percentage of broken kernels, and thus decreased head rice yields. A number of factors throughout rice production, harvest, drying, and storage may affect kernel strength.

Prior to harvest, insect damage and diseases such as rice blast or sheath blight may result in weakened kernels, thus decreasing milling quality[2]. Another production factor that can impact rice quality is ambient temperature during kernel development. Research conducted in controlled-environment chambers showed that increasing nighttime air temperatures during kernel reproductive stages can dramatically increase chalkiness and reduce head rice yields[3, 4]. Chalkiness, illustrated in Figure 5.3-1, reduces kernel strength and thus directly relates to milling yield reduction, in terms of both milled and head rice yield.

Field research has confirmed and extended these findings. Ambardekar et al.[6] developed an analysis showing that increasing levels of nighttime air temperatures (defined as those occurring between 8:00 p.m. and 6:00 a.m.) during certain kernel reproductive stages were strongly correlated to increasing levels of chalkiness and reduced head rice yields, but the degree of susceptibility was cultivar-dependent. Lanning et al.[7] applied this analysis to field data collected from six cultivars grown in 2007 through 2010 at locations from northern to southern Arkansas, USA. Figure 5.3-2, from this analysis, illustrates that in general, as nighttime air temperatures during the R-8 reproductive stage[8] increased, chalk values increased and head rice yields correspondingly decreased dramatically, particularly in some cultivars. It is especially noted that the data from 2010 generally represented extreme nighttime air temperatures for the U.S. Mid-South, with historically high chalk levels and low head rice yields.

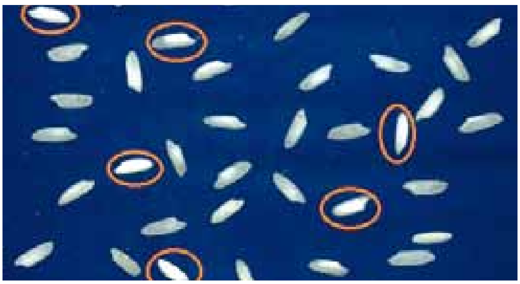

Fig. 5.3-1: Rice kernels exhibiting chalk, which appears as an opaque white region in contrast to translucent regions. Chalk is thought to be caused by loose packing of starch granules during the grain-filling stages, and may affect all or part of the kernel. Source: Ref. 5

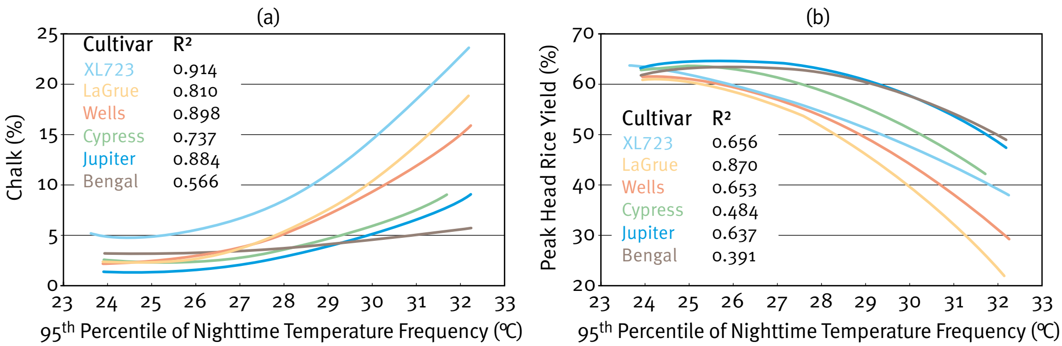

Fig. 5.3-2: Relationships of chalk values (a) and peak head rice yields (b) to 95th percentiles of nighttime air temperature frequencies during the R-8 stage[8] for the indicated cultivars grown from 2007 to 2010 in Arkansas, USA. Source: Ref. 7

The most dramatic impact on milling quality is that peak head rice yields, obtained by harvesting at moisture content levels corresponding to maximum yield (see below), can be reduced substantially when high nighttime air temperatures occur during kernel filling. This effect can help explain previously inexplicable differences in milling yield. Figure 5.3-3 provides such an example, in which head rice yields of the same cultivar, grown during 2008 in two Arkansas, USA locations (Pine Tree in the northern and Stuttgart in the southern parts of the state), were as much as four percentage points different; this difference was attributed to nighttime air temperature effects.

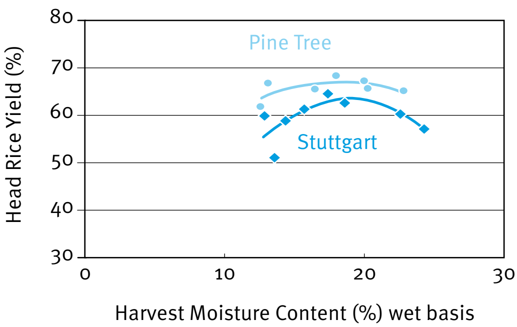

Fig. 5.3-3: Illustration of head rice yields of long-grain cultivar Wells harvested over a range of moisture contents at northern (Pine Tree) and southern (Stuttgart) locations in Arkansas, USA during 2008. The difference in head rice yields between the two lots is attributed to elevated nighttime air temperatures that were observed in Stuttgart during the grain-filling stages. Source: Ref. 5

Of additional note, Lanning et al.[9] showed strong correlations between many compositional/functional properties and nighttime air temperatures during kernel development. Of particular relevance to this chapter, brown rice total lipid content, reasoned to be an indicator of the thickness of rice kernel bran layers, was shown to linearly increase with increasing nighttime air temperatures, thus impacting the rate at which rice kernels are milled to a specified degree of milling level. As illustrated by Lanning and Siebenmorgen[10], differences in milling rate among samples can greatly impact milling yield comparisons.

As rice matures, milling yield typically varies with the degree of maturity of the rice kernels, often indicated by the moisture content at which rice is harvested. This is fundamentally due to the fact that during the maturation and in-field dry-down processes, individual kernels on a panicle will exist at very different moisture contents, representing various maturity and kernel strength levels[11]. An example of this is illustrated in Figure 5.3-4, which shows that when the average, bulk moisture content is 22.7 % (wet basis), a large range of individual kernel moisture contents exists. Individual kernel moisture content distributions usually have multiple modes when rice is harvested at 16 % moisture content or greater. These distributions transition to single modes at lower moisture contents, yet there is typically still a large range in kernel-to-kernel moisture contents, as is shown in Figure 5.3-4 for rice at a bulk moisture

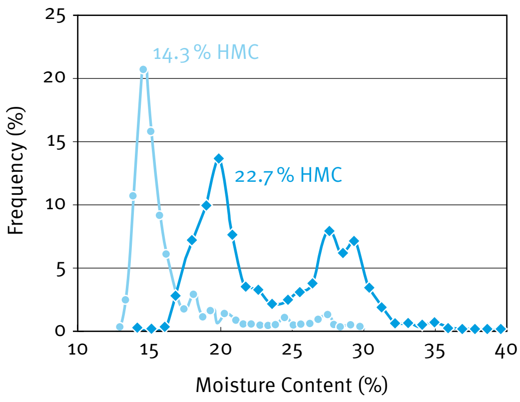

Fig. 5.3-4: Individual kernel moisture content distributions within rice panicles (composite of kernels from five panicles) of medium-grain cultivar Bengal at average harvest moisture contents (HMCs) of 22.7 % and 14.3 (%, w. b.) from Stuttgart, Arkansas, USA. Source: Ref. 5

content of 14.3 %. As such, at a given point in time during harvest, some kernels on a panicle may be at much different moisture content than others[12, 13] and thus will respond differently to ambient air and environmental changes, which can dramatically impact milling yield.

Individual kernel moisture content distributions at harvest can be used to explain milling yield levels of rice lots, in that the distributions can be utilized to quantify the percentage of immature kernels, often considered as those kernels with moisture contents greater than 22 %, as well as the percentage of "dry" kernels, often referring to those kernels with moisture contents less than 14 %. Immature, or "green" kernels, illustrated in Figure 5.3-5, can be a source of milling yield reduction since these kernels are typically weak in structure and often break during milling[14].

Rapid rewetting of low-moisture content kernels, such as would occur through exposure to rain or high ambient air relative humidity, typically causes dry kernels to expand rapidly at the kernel surface. However, because an extended duration is required for the moisture to migrate inward, the kernel center cannot immediately expand, creating a stress differential from the interior to the surface of the kernel that ultimately results in material failure and fissure formation. Fissured kernels caused by rapid moisture adsorption, as illustrated in Figure 5.3-6, typically break apart during milling, reducing head rice yield.

Figure 5.3-7 shows how the percentage of fissured kernels in samples increases as the moisture content at which rice is harvested decreases; the propensity for kernels to fissure due to moisture adsorption increases as the kernel moisture content decreases. As shown in Figure 5.3-7, the percentage of fissured kernels can increase approximately exponentially as rice dries in the field[15]. It is to be noted that the fissured-kernel percentage is not always perfectly correlated to the percentage of low-moisture content kernels, since fissuring by moisture adsorption is dependent upon moisture being supplied by the environment in some manner, such as precipitation or high air relative humidity.

An example of the relationship between head rice yield and individual kernel moisture content distributions is given in Figure 5.3-8. The head rice yield versus harvest-moisture content curve of Figure 5.3-8 indicates a parabolic relationship, with a peak head rice yield at approximately 20 %

Fig. 5.3-5: Immature or "green" kernels on a panicle. Inset shows immature kernels after harvest and hulling; such kernels are generally weak in structure and prone to breaking. Source: Ref. 5

Fig. 5.3-6: Fissures in a kernel caused by rapid moisture adsorption. Source: Ref. 5

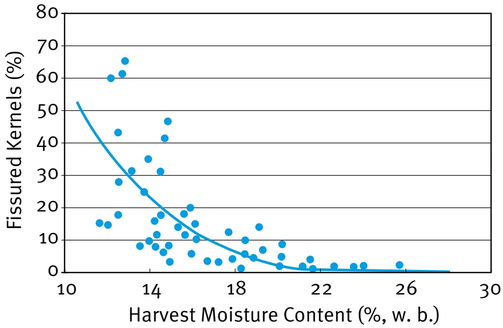

Fig. 5.3-7: Fissured kernel percentages as a function of harvest moisture content. Source: Ref. 15

moisture content. Figure 5.3-8 also shows that head rice yields decline at harvest moisture contents greater than the peak of 20 %, postulated to be due to the increasing presence of thin, immature kernels, depicted in Figure 5.3-8 by the percentage of kernels with moisture contents greater than 22 %. The decline in head rice yield at low harvest moisture contents corresponds to the increasing percentage of kernels with moisture contents less than 14 %, which would likely be fissured due to rapid moisture adsorption.

Trends in head rice yield across harvest moisture contents over a five-year period for multiple cultivars and locations in Arkansas, USA are given by Siebenmorgen et al.[16]. Most of these trends are parabolic in

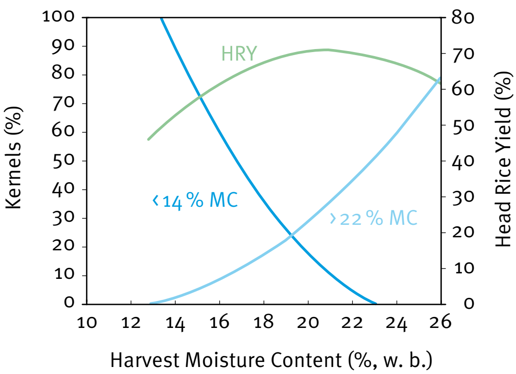

Fig. 5.3-8: Relationships of percentages of kernels at moisture contents (MCs) › 22 % or ‹ 14 % and head rice yields (HRYs) to harvest MCs for long-grain cultivar Drew harvested at Keiser, Arkansas, USA. Source: Ref. 15

form, allowing the harvest moisture content at which head rice yield is maximum to be estimated. The harvest moisture content at which head rice yield is maximum, under Arkansas weather conditions, was reported to be approximately 19 to 21 % for long-grain cultivars and 22–24 % for medium-grains[16], while for California, USA conditions, Mutters and Thompson[17] recommended harvesting medium-grains at greater than 21 %. Based strictly on maximizing head rice yield , it is generally recommended to harvest rice at these optimal moisture contents. However, when considering that drying costs generally increase dramatically with harvest moisture content, the economic optimum harvest moisture content may be slightly less than the optimal moisture content for maximizing head rice yield, depending on drying charges and the relative value of head rice to brokens, as presented by Siebenmorgen et al.[18].

A considerable amount of research has also shown that drying and storage conditions may impact rice milling characteristics and yield. For example, Daniels et al.[19] found significant interactions among drying, tempering, and storage conditions and their effects on milling yield and functionality, suggesting that changes in rice physicochemical properties are complex functions of post-harvest conditions. The reader is referred to Kunze and Calderwood[20] and Siebenmorgen et al.[21] for a more complete review of the impact that drying and storage can have on milling yield.

5.4 Laboratory assessment of milling quality

The Federal Grain Inspection Service (FGIS), an agency within the USDA, provides a methodology for conducting a milling yield analysis, which calls for a representative, 1-kg sample of rough rice to be hulled using a laboratory huller with specified roller clearances. The resulting brown rice is to be milled using an "approved milling device" for a 30-second duration[1]. Broken kernels are then typically removed from head rice by some means. A common laboratory method for separating broken kernels from head rice employs a series of oscillating, inclined, indented plates with indentions sized according to the type of rice (short-, medium-, or long-grain) to be sorted. The plates oscillate gently, which causes the greater-mass head rice to be conveyed into a collection pan before the lesser-mass broken or underdeveloped kernels. Recent advances in imaging technology have allowed the introduction of laboratory systems that estimate the percentage of head rice and broken kernels in a milled-rice sample, based on kernel dimensional analysis rather than physical separation. While these imaging systems are effective in giving a fairly rapid estimation of head rice yield, separation of broken kernels is often necessary in laboratory settings in order to produce the head rice required for other quality and functionality assessments.

Industry and research personnel often deviate from the overall FGIS milling procedure. In particular, the McGill #3 mill, which currently is the formally-approved milling device by the FGIS, requires a 1-kg rough-rice sample size. However, this amount is often greater than is available, especially in research settings. Several companies have developed laboratory mills capable of milling lesser quantities of rice, including a test tube method designed for samples less than 5 g[22]. Perhaps the most commonly-used laboratory-scale mill in the U.S. rice industry is the McGill #2 mill, illustrated in Figure 5.4-1. This batch-type mill has gained popularity over the McGill #3 because of its lower initial cost, as well as lower energy and sample size requirements. Andrews et al.[23] reported that the McGill #2 mill may be used with rough rice sample quantities as small as 125 g (yielding a resultant brown rice mass of approximately 100 g) and that settings

Fig. 5.4-1: McGill #2 laboratory-scale rice mill

could be adjusted to produce results equivalent to the McGill #3. However, when compared to a commercial milling system, Graves et al.[24] found that the McGill #2 produced a lesser head rice yield, smaller kernel dimensions, and a lower incidence of bran streaks, indicating a more aggressive milling treatment than a multi-pass, continuous-flow, commercial milling process. Bennett et al.[25] reported that rice moisture content and milling duration were the most significant variables affecting the degree of milling achieved by a McGill #2 mill.

As mentioned previously, a sample's degree of milling reflects the degree to which bran layers are removed from the caryopsis, or conversely, the amount of bran remaining on the kernel after milling. This is an important concept in the rice industry, because the degree of milling is known to affect rice milling quality indices, such as head rice yield[26, 10], as well as processing characteristics, including the energy required to cook rice[27, 28], cooked rice texture[29], and pasting parameters[30]. Establishing a target degree of milling varies with end-use application and consumer preference. For example, manufacturers of ready-to-eat cereal typically specify a more lightly-milled rice (greater surface lipid content) than that used for household cooking applications. Based on the observation that rice becomes lighter in color as the degree of milling increases[24], the FGIS degree of milling scale is based primarily on milled rice kernel color and visual appearance, a sample's degree of milling is classified as one of three categories: reasonably well-milled (darkest in color), well-milled, and hard-milled (lightest in color)[1].

This classification system is rather subjective and may be skewed by other factors, such as genetics and pre-/post-harvest environmental conditions, which also affect kernel color[31]. Instrumental optical or color measurements, such as those obtained by the Satake Milling Meter (Satake Corporation, Hiroshima, Japan), the Kett Whiteness Meter (Kett Laboratory, Tokyo, Japan) or the Hunter Colorflex system (Hunterlab, Reston, Virginia, USA) can minimize subjectivity in color assessment, but to date, instrumental readings have not been standardized to the FGIS degree of milling categories, nor do they address genetic/environmental effects on color.

5.5 Surface Lipid Content as a Measure of Degree of Milling

A more objective assessment of the degree of milling can be made by quantifying the surface lipid content, which is the mass of lipid remaining on the surface of kernels after milling, expressed as a percentage of the milled, head rice sample mass[32]. As the surface lipid content decreases, the degree of milling is said to increase. Correspondingly, as the degree of milling increases, both milled and head rice yield decrease. During the milling process, there are several factors that influence the degree to which individual kernels, which collectively represent the bulk population of kernels, are milled. Among them are intrinsic factors, such as kernel characteristics and the moisture content of the rice at the time of milling[10], which are discussed in greater detail in the following paragraphs. Mill settings and conditions also play a large role in determining the degree of milling, including the duration of milling and the pressure applied to kernels within the milling chamber[23].

Surface lipid content may be measured by conventional lipid extraction procedures, such as those using Goldfisch or Soxhlet methods, and various automated or modified versions of these[32, 33]. However, these methods are costly, requiring labor-intensive sample preparation and chemical reagents, and do not lend well to online use in a production environment. Therefore, much of the rice industry is moving toward more rapid, indirect methods for estimating the surface lipid content, of which the most common is near-infrared spectroscopy (NIRS). This technology has been shown to accurately predict the surface lipid content[34, 35], as well as other parameters including apparent amylose[36], protein[37], and moisture content[38].

There are many factors that impact the rate at which the surface lipid content of a bulk sample, and the individual kernels comprising a sample, decreases as milling progresses. For example, when milling in commercial-scale systems, Chen and Siebenmorgen[39] and Chen et al.[40] reported that within a given rice bulk, thick kernels will be adequately milled before thinner kernels. However, when the overall bulk lot surface lipid content reached well-milled levels, there was little to no difference in the surface lipid contents of thick to thin kernels.

Additionally, the rice cultivar or cultivar mix also affects milling behavior. Rice cultivars inherently differ in physical attributes, including bran thickness and kernel shape, size, hardness, and topography. These characteristics impact the relative ease with which bran is removed during milling, and thus affect the milling duration required to reach a specified degree of milling/surface lipid content. Cultivars with deep kernel-surface grooves are likely to have bran remaining in the grooves after milling[41] and therefore require more milling pressure or longer milling durations than kernels with smooth surfaces in order to achieve a desired degree of milling. Milling for longer durations results in greater removal of bran, as well as endosperm, thereby reducing head rice yield[42].

In addition to kernel-surface topography, other cultivar differences can impact milling behavior. Siebenmorgen et al.[43] and Lanning and Siebenmorgen[10] reported that hybrid cultivars generally reached a target surface lipid content in a shorter duration than pureline cultivars. These findings were attributed to lesser brown rice total lipid content, as well as greater bran removal rates, in hybrid cultivars. The trends in head rice yield vs. surface lipid content regression slopes, illustrated in Figure 5.5-1, suggest that head rice yield reduction rates vary only slightly with cultivar[10]. As alluded to above, total lipid content can be impacted by nighttime air temperatures during kernel formation; thus year-to-year and location-to-location differences within cultivars can be expected.

The rice moisture content at the time of milling plays a significant role in the bran removal rate. Several studies[23, 44, 45] show that for a given milling duration, as milling moisture content increases, head rice yield decreases; this decrease is attributed to greater bran removal rates, and possibly inadvertent endosperm removal rates as well, at greater moisture contents. Reid et al.[42] and Lanning and Siebenmorgen[10] showed that milling moisture content significantly influenced the rate at which head rice yield changed with respect to the degree of milling as a function of the surface lipid content (Fig. 5.5-2).

The brown rice temperature at the time of milling also impacts bran removal. Archer and Siebenmorgen[46] found that when milling in a McGill #2 mill for set durations, as the initial rice temperature decreased, both the milled and head rice yields increased,

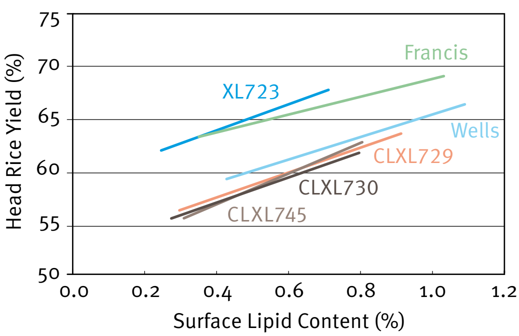

Fig. 5.5-1: Head rice yield vs. head rice surface lipid content of Wells, Francis, XL723, CL XL729, CL XL730, and CL XL745 cultivars milled at a rough rice moisture content of approximately 12.5 (%, w. b.) for 10, 20, 30, and 40 s using a McGill #2 laboratory mill. Source: Ref. 10

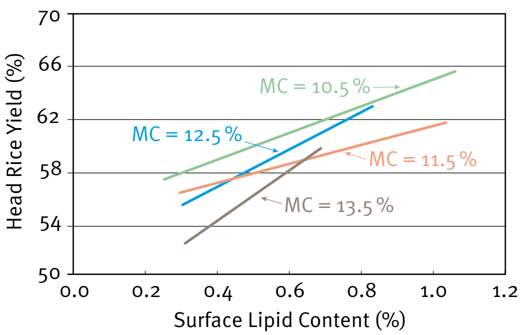

Fig. 5.5-2: Head rice yield vs. head rice surface lipid content for the CL XL745, long-grain cultivar milled at rough rice moisture contents of approximately 10.5 %, 11.5 %, 12.5 %, and 13.5 (%, w. b.) for 10, 20, 30, and 40 s using a McGill #2 laboratory mill. Ref. 10

indicating greater bran removal resistance, greater surface lipid content levels, and correspondingly greater milled rice and head rice masses. This phenomenon appeared to be almost entirely attributable to changes in the degree of milling, since the differences in yields were negated when the milling yield values were adjusted to a constant degree of milling.

The impact of rice moisture content and temperature on bran removal may be explained by Kohlwey[47], who speculated that bran removal is facilitated by a micro-scale gelatinization of starch. This micro-gelatinization occurs at the surface of the endosperm due to increased temperature resulting from friction in the milling process. Greater kernel temperatures are likely to enhance or accelerate this effect. Further, greater moisture content results in decreased starch gelatinization temperature, which may allow greater ease of bran removal.

5.6 Accounting for Surface Lipid Content when Determining Milling Yield

In assessing milling yield, it is important to have an understanding of how the above variables impact the rate of bran removal and surface lipid content change, and how this influences the relationship between head rice yield and surface lipid content. As such, the surface lipid content should be considered when conducting laboratory milling analyses in order to equitably compare head rice yield and subsequent measurements of functional properties that are affected by the degree of milling. When the surface lipid content is measured over a range of milling durations, the relationship between head rice yield and the surface lipid content can be illustrated graphically, and is sometimes referred to as a "millability" curve. Figure 5.5-1 is an example of such a curve, showing that head rice yield is directly and linearly correlated to the surface lipid content[10, 42, 43]. The slope of the regression curve can vary among cultivars and lots, depending on the afore-mentioned variables.

Cooper and Siebenmorgen[26] evaluated the millability curves of 17 rice lots comprising multiple cultivars, harvest years, harvest locations, and storage conditions in an attempt to develop a method for adjusting head rice yield to account for variation in the degree of milling. Across all lots, the average head rice yield vs surface lipid content slope was 9.4; i. e. head rice yield changed by 9.4 percentage points for every 1.0 percentage point change in surface lipid content. In more practical terms, a decrease of 0.1 percentage points in surface lipid content resulted in a decrease in head rice yield of nearly 1.0 percentage point. A follow-up study by Pereira et al.[48] further refined this adjustment method by calculating separate slopes for medium- and long-grain cultivars as 8.5 and 11.3, respectively. Recent research has shown that among long-grain cultivars, some hybrid cultivars demonstrate a greater rate of change in head rice yield with respect to the surface lipid content, i. e., greater millability slopes, than do some purelines[10]. While it stands to reason that individual millability slopes could be calculated for each and every cultivar, it is impractical to do so, since in many industry settings, cultivars are comingled, often based on kernel length. More important to consider is that these factors, when applied to commercial milling, have significant economic impact in terms of the total amount of head rice produced, the rate at which it is produced, and the energy required for milling. General implications are that a lesser degree of milling results in greater head rice yield, and that greater throughput may be achieved in milling certain cultivars vs. others.

5.7 Impact of Surface Lipid Content on End-Use Functionality

As with milled rice yield and head rice yield, most post-milling properties are impacted by the degree to which rice is milled. Laboratory milling systems are often used to produce representative samples of milled and/or head rice from which functional, sensory, and nutritional tests can be performed. Proximate analyses, such as protein, lipid, and starch contents, are often used as a basis for estimating or explaining end-use performance of a rice lot. Further characterization of the starch fractions may include estimates of amylose and amylopectin contents. Viscometry or differential scanning calorimetry procedures, requiring small amounts of rice that can be produced in laboratory mills, may also be used to characterize milled rice functionality and processing behavior.

Since rice protein and lipid contents are greater in the bran, while the endosperm consists primarily of starch, milling effectively alters the relative proximate composition of the milled kernel by increasing starch content and decreasing protein and lipid contents. The degree to which the composition is altered depends on the degree of milling. Considerable research has been conducted to examine the effects of the degree of milling level on rice functional[30], textural[27, 28, 49], and nutritional[50] properties.

Since most end-use processes include a cooking step, hydration characteristics of milled rice kernels are of great importance. Desikachar et al.[49] demonstrated that bran forms a moisture barrier on the surface of kernels, which can impede water uptake, and suggested that a minimum degree of milling was required in order for rice to absorb water unhindered. Brown rice, which is consumed with germ and bran layers intact, requires a much greater cooking duration in order to achieve adequate hydration[27, 28], although processing technologies have been developed to modify the bran layer, thus improving the rate of hydration while retaining the healthful benefits associated with the germ and bran[51, 52].

The presence of protein and lipids has also been shown to affect starch functionality and pasting properties. Proteins and lipids are known to form complexes with amylose and amylopectin, which may restrict the swelling and leaching of starch granules in solution, thus affecting gelatinization and retrogradation processes. However, the functional effects of these interactions vary with the amount of amylose present, the amylose to amylopectin ratio, and the types/concentrations of lipids present[53, 54, 55]. Perdon et al.[30] reported that peak viscosities increased with increasing degree of milling (i. e. decreasing surface lipid content), while final viscosities showed inconsistent and sometimes insignificant effects. This study also noted that amylase, an enzyme that breaks down amylose, is present in the bran layer; therefore, rice milled to a greater degree of milling is reasoned to have less amylase, and thus, greater paste viscosity.

Rice is a rather unique grain in that it is commonly consumed as an intact kernel; therefore, cooked rice texture and flavor are important quality parameters. Cooked rice textural properties are affected by the chemical composition of milled rice, as a function of the degree of milling. Factors involved in cooked rice texture are numerous and varied, as are the methods used to analyze them[27, 28, 56, 57, 58]. Textural properties may be assessed by human subjects, as with panels trained in descriptive analysis, or by instrumental methods. Researchers generally consider hardness and stickiness to be the best indicators of cooked rice texture[59, 60], but other attributes, such as adhesiveness, cohesiveness, toothpack, and others may also be measured. A thorough review of the many sensory and instrumental techniques used to evaluate cooked rice textural properties can be found in Champagne et al.[61].

Since water uptake is affected by the degree of milling, it is clear that the degree of milling will influence textural properties, as shown by Saleh and Meullenet[29]. This study indicated that water uptake was impeded in lesser-milled rice (i. e., greater surface lipid content) due to increased protein content, and to a lesser extent, increased surface lipid content. These findings are supported by Okadome et al.[62], who reported that protein was the most important factor in determining surface hardness of cooked rice, and by Eliasson and Krog[63], who evaluated the role of lipids in rice texture and pasting properties. Research suggests that lipid-starch and protein-starch complexes, which form during the cooking process, restrict water uptake, resulting in a firmer kernel texture[64].

Greater degrees of milling are associated with greater apparent amylose contents[65], since starch content, and the amylose fraction of the starch, increase toward the core of the kernel[66]. As a result, amylose and degree of milling are often shown to produce similar relationships with regard to functional and sensory characteristics. Mohapatra and Bal[56] reported comparable effects of the degree of milling and amylose on water uptake ratio, length and volume expansion ratios, and cooking duration, but found contrasting effects on adhesiveness and hardness.

Champagne et al.[67] found that the degree of milling had a significant effect on flavor-attribute intensities when comparing "regular" to "deep-milled" samples (whiteness scores of 40 and 49 ±2, respectively). However, Billiris et al.[27, 28] reported no significant differences in flavor among rice samples with milling degrees ranging from 0.15 % to 0.55 % surface lipid content. Further, these studies determined that cooking duration was not significantly affected within this surface lipid content range, suggesting that rice could be milled to lesser degrees without compromising cooking or sensory characteristics.

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