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Application of X-ray Imaging as a Technique for Fissure Detection in Rough Rice Kernels

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Application of X-ray Imaging as a Technique for
Fissure Detection in Rough Rice Kernels

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by

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Abstract

Fissured rice kernels break during milling, leading to head rice yield (HRY) reductions. Conventional fissure detection instruments cannot be used to observe fissures in rough rice kernels, the form in which rice in normally dried and stored. X-rays can penetrate hulls allowing visualization of the internal structure of a rough rice kernel. This study evaluated the capability of X-ray imaging to adequately detect fissures in rough rice and established a correlation between HRY and the fissured kernel percentage (FKP) in a rough rice sample. Fifteen long-grain rice cultivars, harvested in Arkansas in 2015 and 2016 were dried using heated air at 60ºC, 10% relative humidity (RH) for various combinations of drying durations and post-drying treatments that resulted in varying degrees of fissuring and HRYs. Fissure detection was conducted using an X-ray system with rough rice and compared to that of a grainscope, a conventional fissure detection instrument, with brown rice. A strong correlation (R^2 = 0.95) was shown to exist between sample HRY and the FKP of the rough rice sample after drying, resulting in a regression equation that could be used to estimate HRY. Having confirmed the impact of fissured kernels on HRY, the X-ray system, with an augmented drying apparatus, was used to evaluate the impact of kernel thickness and moisture content (MC) on rice fissuring. Two long-grain rice cultivars were harvested in Arkansas in 2016, each at two MC levels (high and low), and fractionated into three thickness fraction sub-lots (thin, medium, and thick). The fissuring susceptibility of kernels from each sub-lot was evaluated during drying. Generally, with increase in kernel thickness, the FKP increased for high-MC lots. In regards to MC, high-MC had greater FKPs than the low-MC lots. Overall, these findings show the importance of kernel fissuring to the rice industry, and highlights the role of kernel properties on fissuring during drying.

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Abbreviations

FKP – fissured kernel percentage

HRY – head rice yield

LS – least square

MC – moisture content

MRY – milled rice yield

R – correlation coefficient

R^2 – coefficient of determination

RH – relative humidity

RMSE – root mean squared error

USDA - United States Department of Agriculture

w.b. – wet basis

List of Published Papers

Chapter II: Odek, Z., Prakash, B., & Siebenmorgen, T. J. (in press). X-ray Detection of Fissures in Rough Rice Kernels. *Appl. Eng. Agric.*

Chapter III: Odek, Z., Siebenmorgen, T. J., & Mauromoustakos, A. (under review). Relative Impact of Kernel Thickness and Moisture Content on Rice Fissuring During Drying. *Appl. Eng. Agric.*

I. INTRODUCTION

Head rice yield (HRY) is an important parameter used to determine the milling quality of rice. The United States Department of Agriculture (USDA) defines HRY as the mass percentage of rough rice that remains as head rice after milling, where head rice comprises kernels and kernel fragments that are at least three-fourths of their intact length. Rice kernels with fractures of the endosperm are classified as fissured and are known to break during milling leading to HRY reductions. Therefore, understanding and minimizing rice kernel fissuring is an important goal of the rice industry.

Fissures are known to form in rough rice kernels while in the field, during drying or during storing. Yet, conventional fissure detection instruments and methods can only detect fissures in brown and milled rice kernels. This study utilized X-ray imaging to detect fissures in rough rice, the form in which rice is most often dried and stored.

This study was conducted in two parts: the first part evaluated the ability of X-ray imaging to detect fissures in rough rice kernels and how the fissure detection capability of an X-ray system compares to that of a grainsope, a conventional fissure detection instrument, in brown and milled rice. Additionally, a correlation between sample HRY and the proportion of fissured kernels in the sample was established.

The second part of the study utilized an X-ray system with an augmented apparatus to enable drying and tempering of rough rice kernels within the X-ray system. The X-ray system and the augmented drying apparatus together referred to as a drying system, was used to determine the impacts of kernel thickness and moisture content (MC) on fissuring. Two long-grain rice cultivars were each harvested from the same field at two different MC levels. Each MC-lot was fractionated into three thickness fractions resulting in six sub-lots per cultivar, then the fissuring susceptibility of each sub-lot evaluated during the drying process. Drying experiments were conducted using the drying system by exposing kernels to drying air, tempering and storing for predetermined durations followed by fissure detection.

II. X-RAY DETECTION OF FISSURES IN ROUGH RICE KERNELS

A. Abstract

X-ray imaging is a viable method of fissure detection in rough rice kernels owing to the ability of X-rays to penetrate hulls, thus allowing visualization of internal rice kernel structure. Traditional methods of fissure detection are only applicable for brown and milled rice, and therefore cannot be used to study fissures developed during rough rice drying. In this study, the fissure detection capability of an X-ray system was evaluated and the relationship between head rice yield (HRY), as measured through laboratory milling, and the percentage of fissured rough rice kernels was determined. Long-grain rice lots of various cultivars were dried using heated air at 60ºC, 10% relative humidity (RH) for five drying durations to produce different degrees of fissuring, and then milled to determine HRY. A strong linear correlation (R^2 = 0.95) between HRY and the percentage of fissured rough rice kernels after drying was determined. This correlation confirms the substantial impact that kernel fissures have on milling yields. Overall, these findings show the effectiveness of X-ray imaging in rough rice fissure detection, which could allow for in-situ drying research that may provide a better understanding of kernel fissuring kinetics.

B. Introduction

Fissures in rice kernels are fractures of the endosperm that can either be perpendicular to the long axis of the kernel (Kunze and Calderwood, 2004) or in no specific alignment (Stermer 1968; Bautista et al., 2000). During milling, rice kernels tend to break at the fissure sites. The resulting kernels that are less than three-fourths of an intact kernel are referred to as brokens; the remaining kernels are referred to as head rice. Head rice yield (HRY) is defined as the mass percentage of rough rice that remains as head rice after milling (USDA, 2009). Brokens have a reduced commercial value, typically between 60% - 80% of the value of head rice (Siebenmorgen et al., 2008). Therefore, minimizing kernel fissuring is an important goal of the rice industry.

Fissures can occur in the field due to rapid moisture adsorption by low-moisture content (MC) kernels (Kondo and Okamura, 1930; Kunze, 2008) or after harvest due to improper drying and/or tempering (Kunze, 1979; Schluterman and Siebenmorgen, 2007). Extensive research has been conducted to understand rice fissuring mechanism(s). Banaszek and Siebenmorgen (1990), in a study to determine the effects of moisture adsorption on HRY, observed that exposure of rice at 9% MC[1] to a high relative humidity (RH) of 90% resulted in HRY reductions of over 20 percentage points. Inter-kernel MC differences during storage and/or transportation can also lead to kernel fissuring. Calderwood (1984) observed that mixing of rough rice at 8% MC with rice at ≥17% MC caused severe HRY reductions. Cnossen and Siebenmorgen (2000) presented a hypothesis that addresses rice kernel fissuring during drying and tempering. This hypothesis identifies the role of intra-kernel material state differences on fissure formation. Similarly, Steffe

[1] All moisture content values are expressed on a wet basis.

and Singh (1980) and Iguaz et al. (2006) observed that tempering minimized fissured kernel percentage and resulting HRY reduction.

Fissures in brown and milled rice kernels can be detected using laboratory instruments such as video microscopy systems (Bautista et al., 2000), grainscopes (Cao et al., 2004; Siebenmorgen et al., 2005), and fissure inspection boxes (Iguaz et al., 2006; Bautista et al., 2009). However, these instruments are not applicable for fissure detection in rough rice kernels, the form in which rice is most often dried and stored. X-rays have the capability to penetrate the hull, thereby enabling fissure detection in rough rice kernels. Henderson (1954), using X-ray imaging, showed that the length of small fissures increases as kernels are dried. Kumar and Bal (2007) used X-ray imaging to detect fissures in rough rice kernels and developed a graphical user interface that could enumerate fissures in a rice kernel. Menezes et al. (2011) used X-ray imaging to correlate the extent of fissuring in rice seeds with germination and sprout development. X-ray imagining has equally been used to study defects in other grains. Haff and Slaughter (2004) compared a real-time digital X-ray system to a film-based X-ray system in detection of insect infestation at different insect developmental stages in wheat kernels. The study showed that the film-based X-ray system yielded greater infestation detection percentages from the egg through the 3rd instar stages, with no significant differences being observed in the two instruments from the 4th instar and beyond.

Grainscopes have been widely used as a method of fissure detection due to low cost and portability. Using a grainscope, Cao et al., (2004) showed that electric field treatment of rough rice at 25ºC did not lead to fissuring. Likewise, Siebenmorgen et al. (2005) showed that as drying temperatures increased, fissured kernel percentages increased, with most fissures appearing within 24 h after drying had ceased. Similarly, Hayashi et al. (2015) used a grainscope to develop a method for evaluating differences in fissuring resistance among cultivars. However, to use a grainscope, the hulls have to be removed from kernels, which is a time-consuming process. It is thus appropriate to determine if eliminating the dehulling process by using an X-ray system to detect fissures in rough rice is as reliable as using a grainscope to detect fissures in brown rice.

Currently, laboratory milling is the only method used for measuring HRY, yet, there is an increasing demand for an instrument that can rapidly estimate this parameter. The process of milling and separating head rice from brokens in laboratory milling operations is time-consuming, and therefore, there is a need for a method that can provide rapid HRY estimates without having to mill samples. Research has shown good correlations between the number of fissured brown rice kernels and HRY reduction using a grainscope (Bautista et al., 2009). However, as aforementioned, the use of a grainscope for fissure detection is limited to brown and milled rice kernels. It is thus relevant to determine if X-ray detection of fissures in rough rice improves the prediction of HRY.

The goal of this research was to evaluate X-ray imaging as a method for fissure detection in rough rice kernels. The objectives of this study were:

(1) to develop a method for fissure detection in rough rice kernels using an X-ray system,

(2) to compare the fissure detection capabilities of X-ray imaging in rough rice kernels to that of a grainscope in brown rice kernels, and

(3) to establish a relationship between the percentage of fissured kernels in a rough rice sample and the sample HRY.

C. Materials and Methods

Rice Samples

Fifteen rough rice samples, comprising long-grain cultivars grown in Arkansas, were harvested at MCs ranging from 16% to 24% from the locations indicated in table 1. All samples were cleaned using a dockage tester (XT4, Carter-Day, Minneapolis, Minn.) to remove material other than grain. Each sample was then placed in sealed plastic bags, which were contained in sealed tubs, and stored in a walk-in cooler at 4°C until when used for the experiment.

Table 1. Summary of harvested rice samples.

Year	Location	Cultivar	Harvest MC (%, w.b.)
2015	Keiser, Ark	LaKast	18.2
	Keiser, Ark	XL753(a)	17.0
	Keiser, Ark	CL152	20.8
	Pocahontas, Ark	XL760	20.0
	Pocahontas, Ark	XL753(b)	19.0
2016	Harrisburg, Ark	Aura115	15.9
	Harrisburg, Ark	Cheniere	18.2
	Harrisburg, Ark	CL151	17.9
	Harrisburg, Ark	CLXP766	17.5
	Harrisburg, Ark	XL753	16.6
	Harrisburg, Ark	CLXL745	19.9
	Harrisburg, Ark	CL111	17.0
	Harrisburg, Ark	XL760	16.4
	Harrisburg, Ark	XL723	19.2
	Keiser, Ark	Roy J	23.6

In order to create samples with a range of fissured kernels, rough rice from each cultivar lot was dried for varying durations. Approximately 1 kg of rough rice from each of the 15 lots was removed from the cooler and allowed to equilibrate at room temperature (21 ± 2ºC) before drying. From each 2015 cultivar-lot, four 200-g sub-lots were each dried using air at 60ºC, 10% RH in thin layers on 318 x 227 mm trays with perforated bottoms for two drying durations: 30

min for two sub-lots and 60 min for the other two sub-lots. Similarly, from each 2016 cultivar-lot, five 200-g sub-lots were dried for three drying durations: 0 min for one sub-lot, 20 min for two sub-lots, and 40 min for the remaining two sub-lots. The drying air conditions were maintained by an environmental chamber (ESL 4CA Platinous Temperature and Humidity Chamber, Espec, Hudsonville, Mich.). The chamber is capable of maintain temperature in the range of -35°C to 150°C (±0.5°C) and RH in the range of 6% to 98% (±1%) at an airflow rate of 0.38 m^3 s^{-1}. One of the two sub-lots from each drying duration was tempered in a sealed bag at 60ºC for 2 h immediately after drying and before cooling, whereas the other sub-lot was cooled immediately after drying by exposing the kernels to air at room temperature (21 ± 2ºC). These drying/post-drying treatments are known to produce drastically different degrees of fissuring consequently, a range of HRYs (Schluterman and Siebenmorgen, 2007; Ondier et al., 2012). These treatments are included in the experimental layout diagram in figure 1. Thereafter, all 70 sub-lots were slowly dried to a MC of 12.5 ± 0.5% in a climate-controlled chamber (26ºC, 56% RH) regulated by a standalone conditioner (5580A, Parameter Generation and Control, Black Mountain, NC).

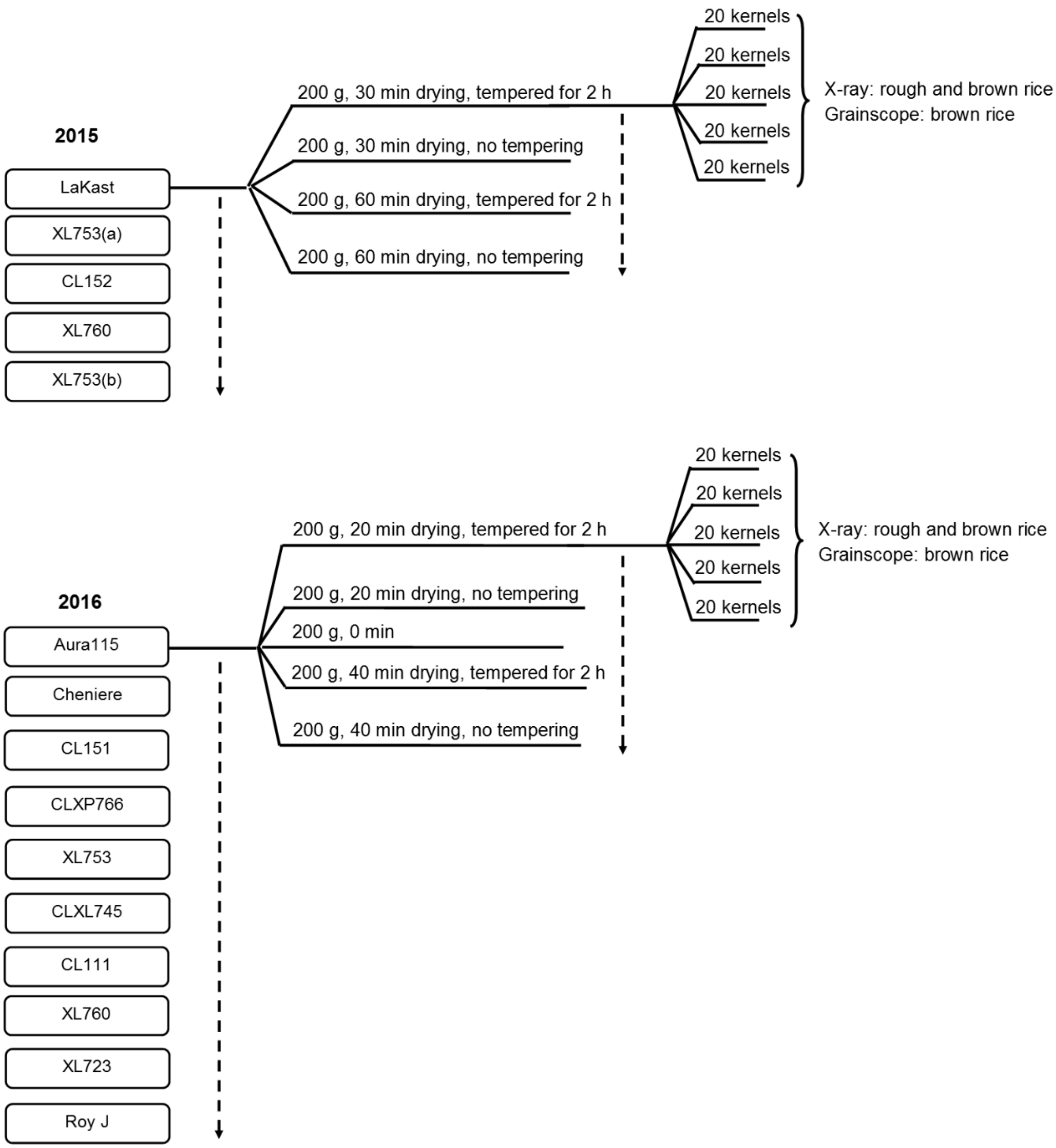

Figure 1. Layout of the experimental design for fissure detection in dried kernels.

Magnification Level

As with most imaging systems, it is important to have a field of view that allows observing a maximum number of kernels. However, there is a tradeoff between the field of view and the degree of magnification, which provides a suitable image resolution for fissure detection. The X-ray system used in this study (UltraFocus 60, Faxitron Bioptics LLC., Tucson, Ariz.) and shown in figure 2a features seven magnification levels, as shown in figure 2b. In order to determine a suitable magnification to provide high-resolution fissure detection, approximately 350 rough rice kernels were placed within the X-ray system on an acrylic sample shelf provided with the system. X-ray images of the kernels were then taken at each available magnification level at 32 KeV energy, 0.34 mA current, and 5.5 s exposure duration by placing the sample shelf in the various slots indicated in figure 2b. All seven images were then visually analyzed and a suitable magnification selected based on image resolution and number of kernels that could be visualized at each magnification.

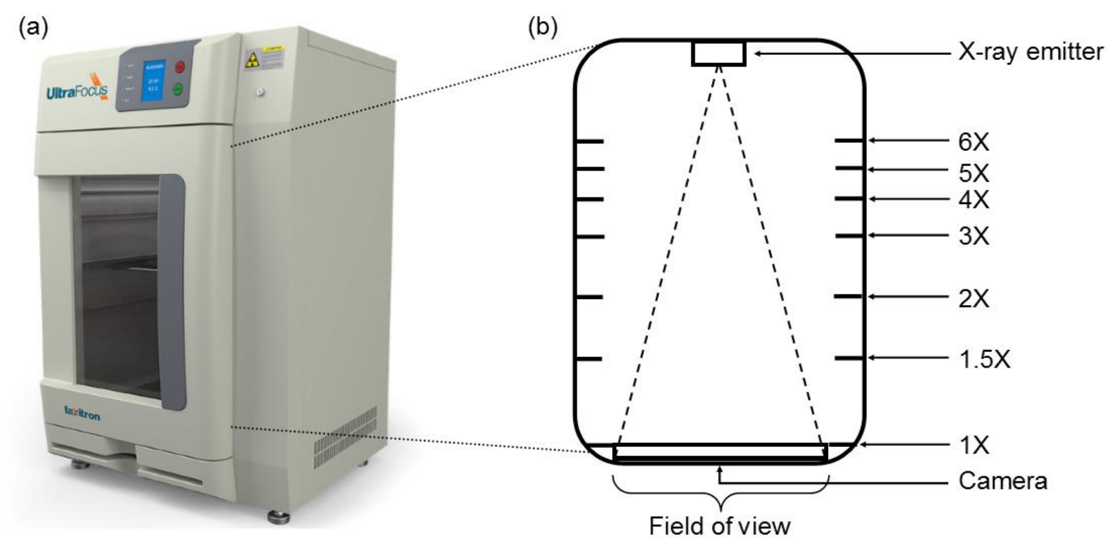

Figure 2. An image of the Faxitron UltraFocus 60 X-ray system (a) and a schematic illustration showing the position of each level of magnification (b). As magnification increases, the field of view decreases.

Kernel Orientation

Identification of an appropriate orientation of rough rice kernels that would allow complete fissure detection was achieved by randomly selecting five fissured rice kernels. The identified kernels were X-rayed at a dosage of 32 KeV, 0.34 mA, and 5.5 s with the kernels placed on the width side (figure 3a), then on the thickness side (figure 3b). The resulting two images were then compared using photo-editing software (Microsoft Paint, Microsoft Corporation, Redmond, Wash.) and an appropriate orientation identified based on visual observation.

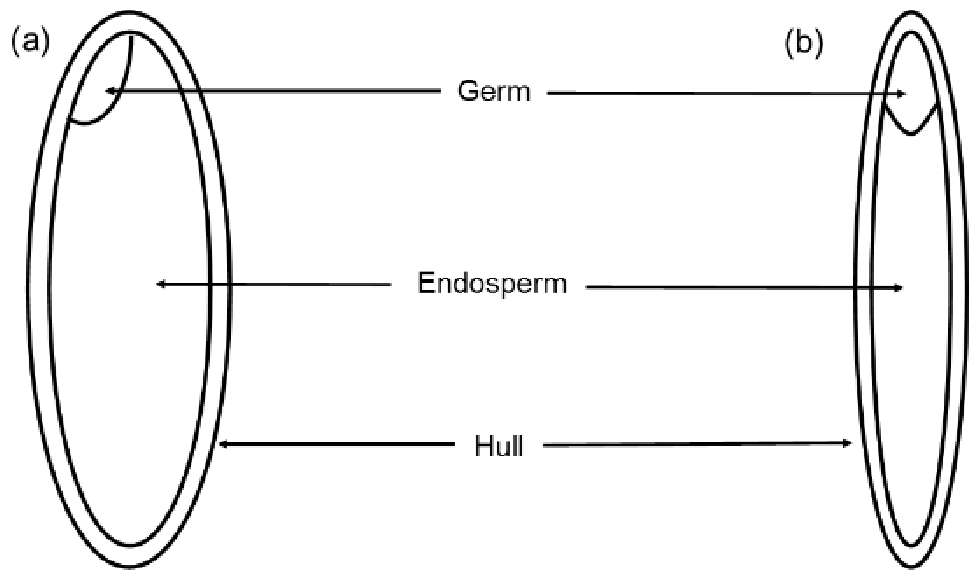

Figure 3. Illustration of the width-side (a) and thickness-side (b) views of a rough rice kernel.

Fissure Detection in Non-dried Kernels

A grainscope detects fissures in brown and milled rice kernels, whereas an X-ray system can detect fissures in rough rice kernels as well. In order to determine how both instruments compare when viewing high-MC, pre-dried kernels, a 100-kernel sample, at MCs near the harvest MCs shown in table 1, was randomly selected from each of the 15 cultivar lots before drying. Each 100-kernel sample was divided into five 20-kernel sub-samples. Fissured kernels were then enumerated using the X-ray system by placing a 20-kernel sub-sample at the 3X magnification position shown in figure 1b at a dosage of 32 KeV, 0.34 mA, and 5.5 s. The same 20-kernel sub-sample was then dehulled by hand to produce brown rice kernels and fissures detected using both the X-ray system, at 3X magnification as above, and a grainscope (TX-200, Kett Electric Laboratory, Tokyo, Japan). This procedure was repeated for the other four sub-samples of the cultivar lot, and then the entire procedure was applied to the remaining 14 cultivar-lots of table 1. For this study, a kernel with a visible fracture of the endosperm was considered a fissured kernel, irrespective of the fracture length.

Fissure Detection in Dried Kernels

Fissures can readily occur due to the drying process. It was thus relevant to determine how the X-ray system and the grainscope compared in detecting moisture desorption fissures. For each sub-lot from each cultivar lot that had been exposed to the various drying and post-drying treatments and then conditioned to 12.5% MC, a 100-kernel sample was selected and divided into five 20-kernel sub-samples. Fissure detection was then conducted using the X-ray system at a dosage of 32 KeV, 0.34 mA, and 5.5 s in rough rice and brown rice, and the grainscope in brown rice for each of the five 20-kernel sub-samples; the experimental layout is shown in figure 1.

Milling Analysis

After the 200-g samples from the drying/post-drying treatments had been dried to 12.5% MC, HRYs were determined by milling a 150-g rough rice sample from each of the sub-lots. These 150-g milling samples were taken from each of the four sub-lots of the five cultivar-lots harvested in 2015 and from the five sub-lots from each of the 10 cultivar-lots harvested in 2016; thus, a total of 70 HRY determinations were made. Of these 70 combinations, 47 were randomly selected and used in deriving an equation relating fissured kernel percentage to HRY, and 23 for validating the ability of the derived equation to predict HRY.

The milling procedure consisted of first dehulling 150 g of rough rice using a laboratory dehuller (Rice Machine THU, Satake Engineering Co., Tokyo, Japan) with a clearance of 0.48

mm between the rolls. The resulting brown rice was then milled for 30 s using a laboratory mill (McGill No. 2, Rapsco, Brookshire, Texas) with a 1500-g mass placed on the lever arm 150 mm from the centerline of the milling chamber. Head rice was then separated from brokens using a shaker table (Grain Machinery Mfg. Co., Miami, Fla.).

Data Analyses

Data analysis was conducted using a statistical package (JMP Pro release 12.0.1, SAS Institute Inc., Cary, NC) to determine a possible correlation between HRY and fissured rough rice kernel percentage detected by the X-ray system. Significant differences among fissure detection capabilities of an X-ray system in rough rice and brown rice, and a grainscope in brown rice were established using Tukey-Kramer Honestly Significant Difference procedure (HSD $P < 0.05$).

D. Results and Discussion

The effect of increasing magnification on image resolution is shown in figure 4, whereas the effect of magnification on the available field of view is shown in table 2. Figure 4 and table 2 show the tradeoff between the number of kernels that can be viewed and the resulting image resolution. As expected, with an increase in magnification, the image resolution increases and the available field of view decreases. The 3X to 6X magnification produced high-resolution images at 32 KeV energy, 0.34 mA current, and 5.5 s exposure duration in which fissures in rough rice kernels could be detected (figure 4), corroborating findings by Kumar and Bal (2007) that showed the potential of X-ray imaging to detect fissures in rough rice. Due to the biological variability among individual rice kernels, having a greater field of view is desired to provide a more representative sample. Thus, the 3X magnification was deemed the optimal magnification, yielding high-resolution images that clearly show fissures, yet with an adequate field of view that allows observation of 50 to 70 rough rice kernels per X-ray image.

Table 2. Field of view dimensions and number of kernels that can be viewed for each magnification level in the X-ray system.

Magnification level	Field of view (mm × mm)	Number of kernels
6X	17 × 25	10 - 20
5X	20 × 30	20 - 30
4X	25 × 37.5	30 - 40
3X	33 × 50	50 - 70
2X	50 × 75	150 - 160
1.5X	67 × 100	180 - 250
1X	100 × 150	>350

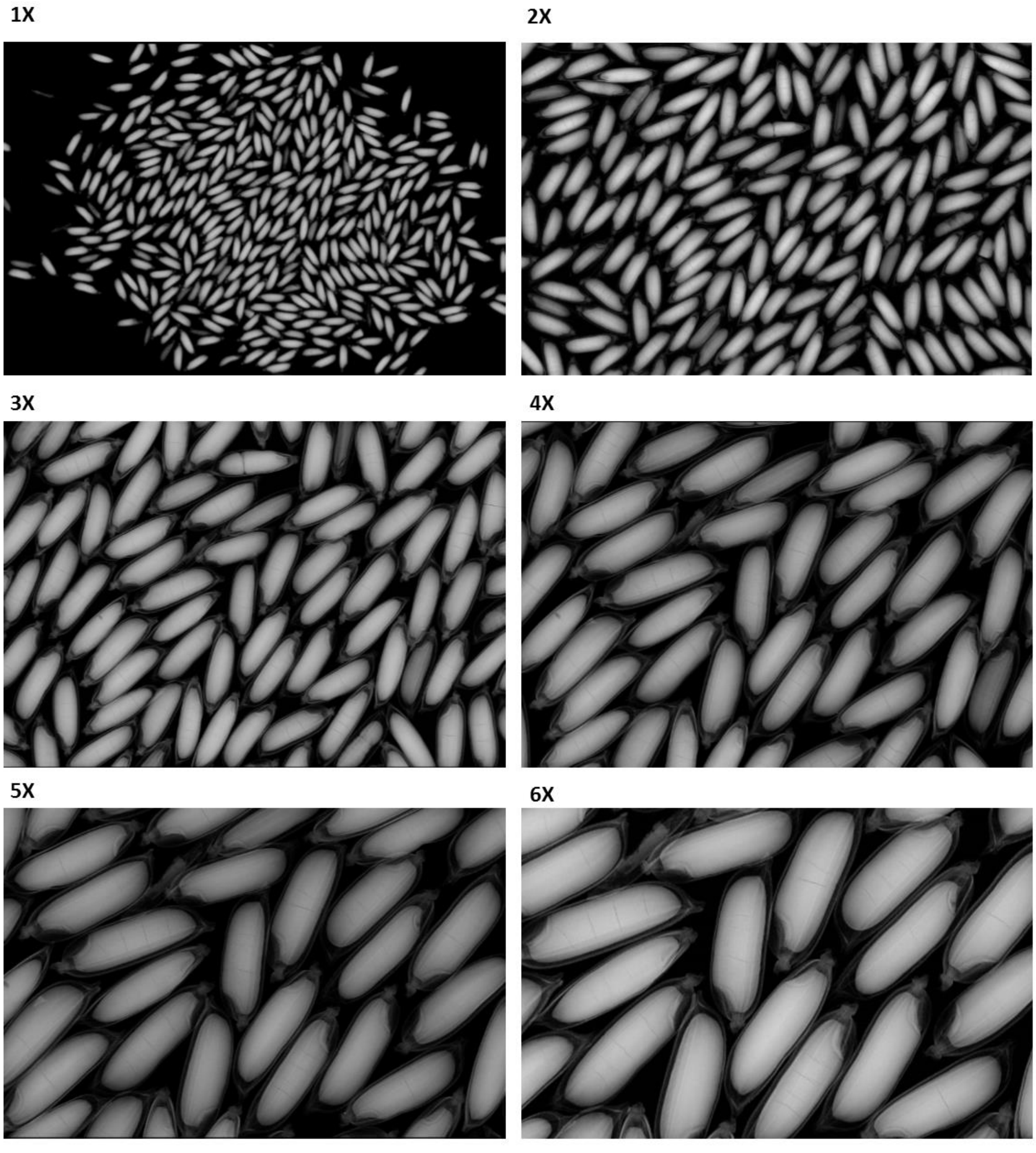

Figure 4. X-ray images of rough rice kernels at 1X, 2X, 3X, 4X, 5X, and 6X magnifications. Each image contains the same set of rice kernels.

Fissures in rough rice kernels were detectable in both the width and thickness orientations. Figure 5 shows an X-ray image of five rough rice kernels positioned in both orientations. All fissures detected in the thickness orientation were also detected in the width orientation. However, not all fissures in the width orientation were detected in the thickness orientation. The fissures that could only be detected on the width side of the kernel are considered surface fissures; this could be the reason why they were not detected on the thickness side. Therefore, placing kernels to allow exposure to the width side when presented for X-ray imaging was deemed appropriate for detecting both surface and internal fissures in rough rice kernels.

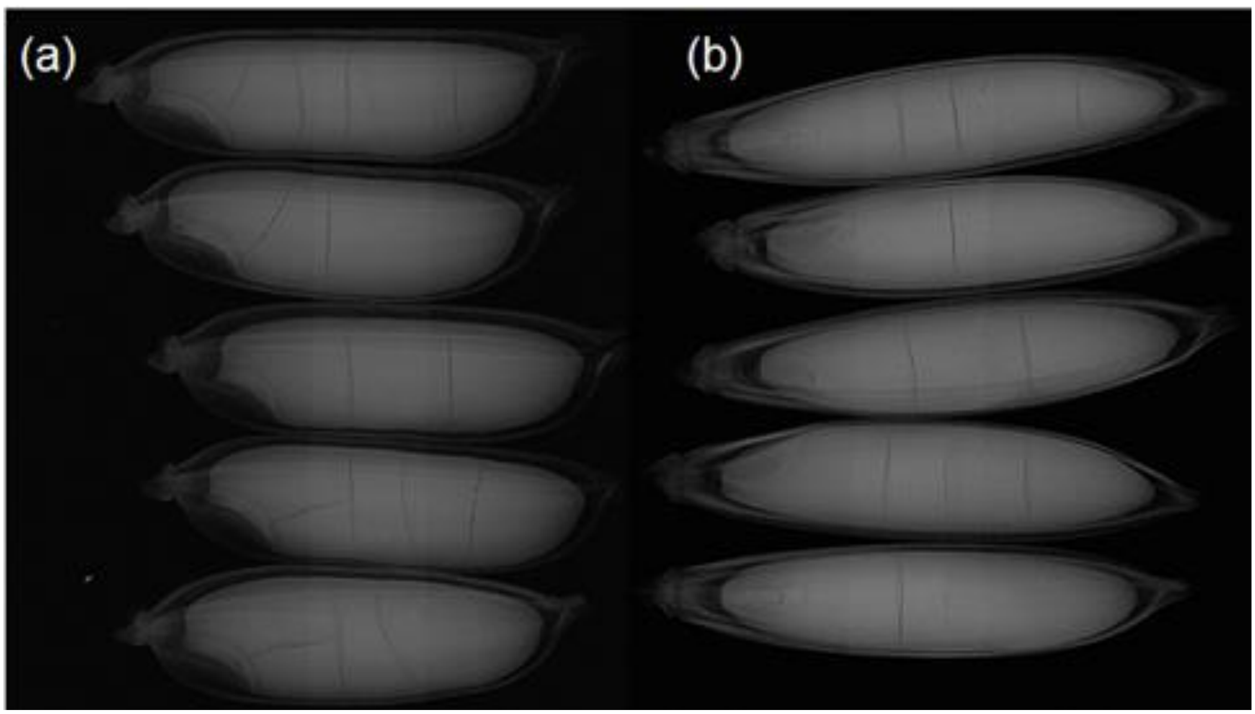

Figure 5. X-ray images of five rough rice kernels placed to be viewed in the width (a) and thickness (b) orientations.

Table 3 shows comparisons among the fissured kernel percentages detected in rough rice and in brown rice by the X-ray system, and in brown rice by the grainscope, for rice at approximately the harvest MCs of the lots listed in table 1. The percentage of fissured kernels detected in rough rice and brown rice by the X-ray system, and in brown rice by the grainscope for the same rice lot were not significantly different, across all cultivar lots as determined by Tukey's HSD procedure. The slight variations in fissured kernel percentages were attributed in part to the biological variation that exists between individual rice kernels within a 20-kernel sub-sample and the capability differences of the X-ray system and a grainscope. Therefore, fissure detection in high-MC rough and brown rice by the X-ray system and in high-MC brown rice by the grainscope were deemed similar. This finding has implications for conducting field research aimed at assessing fissuring levels in high-MC rice; the use of a highly portable grainscope in field applications appears to be comparable to using an X-ray system, which is a more elaborate, laboratory approach.

Table 3. Comparisons among fissure detection capabilities of the X-ray system in rough rice and brown rice, and the grainscope in brown rice for 15 rice lots at various harvest moisture. Each value represents the mean fissured kernel percentage of five 20-kernel sub-samples. Using Tukey's Honestly Significant Difference procedure, there were no significant differences in fissured kernel percentages determined by the three approaches within each cultivar lot.

		Fissured kernel percentage (%)		
Year	**Cultivar**	**Rough rice (X-ray)**	**Brown rice (X-ray)**	**Brown rice (Grainscope)**
2015	LaKast	8	6	4
	XL753(a)	2	2	2
	CL152	4	4	2
	XL760	3	5	5
	XL753(b)	16	18	19
2016	Aura115	15	13	10
	Cheneire	2	2	2
	CL151	4	5	2
	CLXP766	6	7	8
	XL753	6	6	6
	CLXL745	10	10	11
	CL111	3	4	6
	XL760	6	5	5
	XL723	2	3	3
	Roy J	4	5	5

Figure 6 shows the fissure detection comparison between the X-ray system and the grainscope, both using dried brown rice kernels. Figure 6 shows a slope of 1.04 which implies that the two approaches are similar. The root mean square error (RMSE) of 8 percentage points, which is equivalent to 1-2 kernels per 20-kernel sub-sample, indicate that there are marginal differences between the X-ray and grainscope methods of fissure detection in brown rice kernels. There is a general trend, however, showing that the X-ray system detected slightly more fissured kernels than the grainscope, as indicated by the slope of the fitted line which is greater than 1. This trend may be due in part to the different operating principles of an X-ray system and a grainscope; as opposed to an X-ray system that uses ionizing radiation, a grainscope uses visible light and thus, a slight variation in kernel orientation when using a grainscope could make a fissure(s) non-detectable by the human eye.

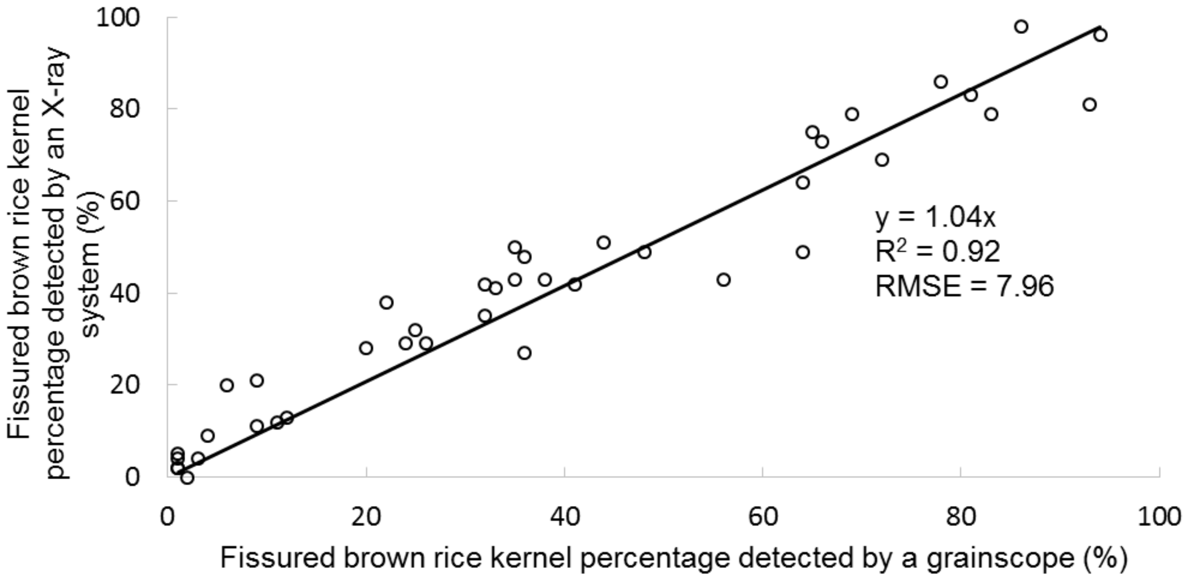

Figure 6. Comparison between fissure detection capabilities of an X-ray system and a grainscope using dried brown rice kernels. Most fissures were created by varying degrees of drying severity and post-drying treatments. R^2 is the coefficient of determination and RMSE is the root mean square error.

Figure 7 compares the fissure detection capabilities of the X-ray system using rough rice and the grainscope using brown rice. Analogous to figure 6, figure 7 shows a slope of 1.03 which implies that the two approaches are similar with few cases where there are great deviations from the fitted line. As was the trend in figure 6 using brown rice kernels, figure 7 indicates a trend that the X-ray system detected more fissured rough rice kernels than was detected in brown rice kernels using a grainscope. At fissured kernel percentages less than 20%, the data points fit closer to the fitted line than when the fissured kernel percentages were greater than 20%. This trend implies that the two instruments have similar fissure detection capabilities at <20% than at >20% fissured kernel percentages.

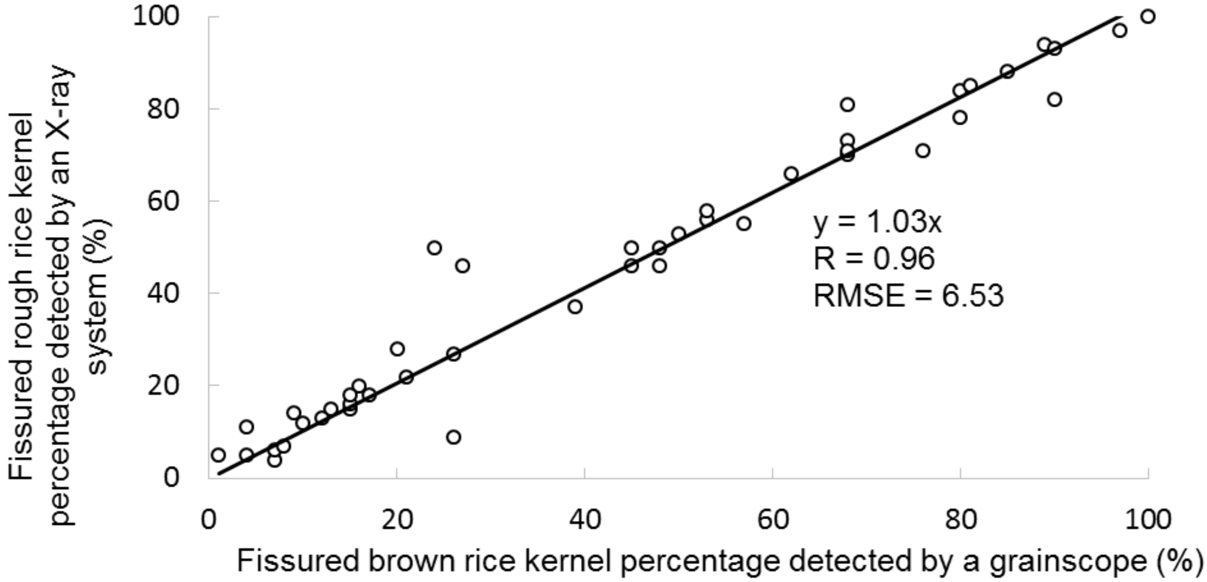

Figure 7. Comparison between fissure detection capabilities of an X-ray system using dried rough rice kernels and a grainscope using dried brown rice kernels. Most fissures were created by varying degrees of drying severity and post-drying treatments. R^2 is the coefficient of determination and RMSE is the root mean square error.

Figure 8 shows the relationship between HRY and the percentage of fissured rough rice kernels detected in dried samples using the X-ray system. The plot shows that HRY is an inverse, linear function of the fissured kernel percentage with a correlation coefficient (R) of -0.97. These findings corroborate those of Iguaz et al. (2006) and Siebenmorgen et al. (2007) wherein an increase in HRY reduction was observed with an increase in the percentage of fissured brown rice kernels observed using a fissure inspection box and a grainscope, respectively. The regression equation relating, HRY to the percentage of fissured rough rice kernels in a dried sample is;

$$y = 63.124 - 0.603x \tag{1}$$

where, y = predicted head rice yield (%) and x = percentage of fissured rough rice kernels in a dried sample as detected using an X-ray system (%).

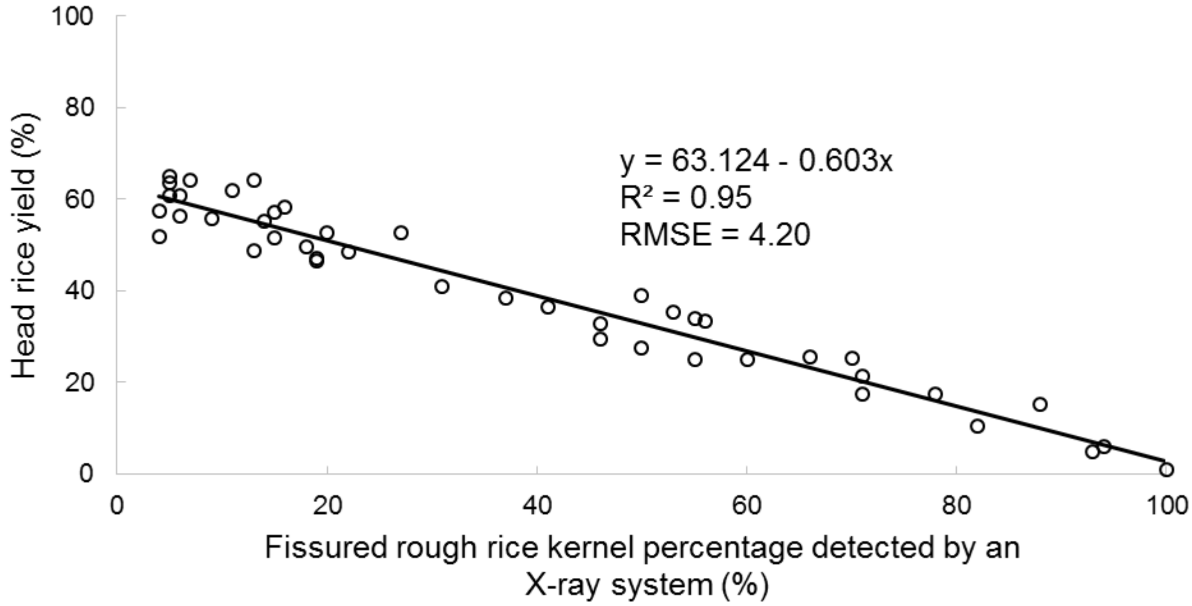

Figure 8. Correlation between head rice yield and fissured rough rice kernel percentage detected by an X-ray system. R^2 is the coefficient of determination and RMSE is the root mean square error.

The coefficient of determination (R^2) (figure 8) implies that 95% of the variability in HRYs can be attributed to the percentage of fissured rough rice kernels in a dried sample. The remaining variability in HRYs can be explained by other factors such as kernel maturity (Lu and Siebenmorgen, 1995), chalkiness (Webb, 1985; Bautista et al., 2010), and insect damage (Arthur et al., 2012). Immature, chalky, and insect-damaged kernels are known to be mechanically-weaker than completely sound kernels and are likely to break during milling. Breakage from these kernels would further reduce HRY than what fissured kernels alone would.

The observed correlation coefficient (-0.97) between HRY and the percentage of fissured rough rice kernels, was greater than the value of 0.87 observed by Bautista et al. (2009) as the correlation between HRY reduction and the percentage of fissured brown rice kernels detected using a grainscope. The improved correlation observed in the current study is attributed to the ionizing-radiation capabilities of the X-ray system, which allowed for more accurate fissure detection, even in rough rice kernels.

In order to validate the ability of equation 1 to predict HRY from the fissured kernel percentage, the HRYs predicted using equation 1, for each of the 23 sub-lots that were allocated as a validation set, were compared to the HRYs determined through laboratory milling. The comparison, shown in figure 9, indicates that equation 1 provided satisfactory HRY predictions since the difference in RMSE of figure 8 (4.20) and that of figure 9 (4.92) is not large. Most data points in figure 9 are above the y = x reference line, an indication that the HRY value predicted using the X-ray-based equation was greater than the value actually measured through a milling analysis by an average of 5 percentage points. Thus, the validation procedure yielded similar trends to the correlation results of figure 8 that produced equation 1. Therefore, the HRY obtained through milling would be expected to be less than that predicted by the equation (eq. 1). This is interpreted to mean that the fissured kernel percentage alone is not the only relevant factor in determining HRY; other kernel imperfections, as mentioned above, could play varying roles in reducing HRY. In spite of this overestimation, equation 1 is still deemed useful in providing rapid estimates of expected HRY without having to de-hull or mill a rough rice sample.

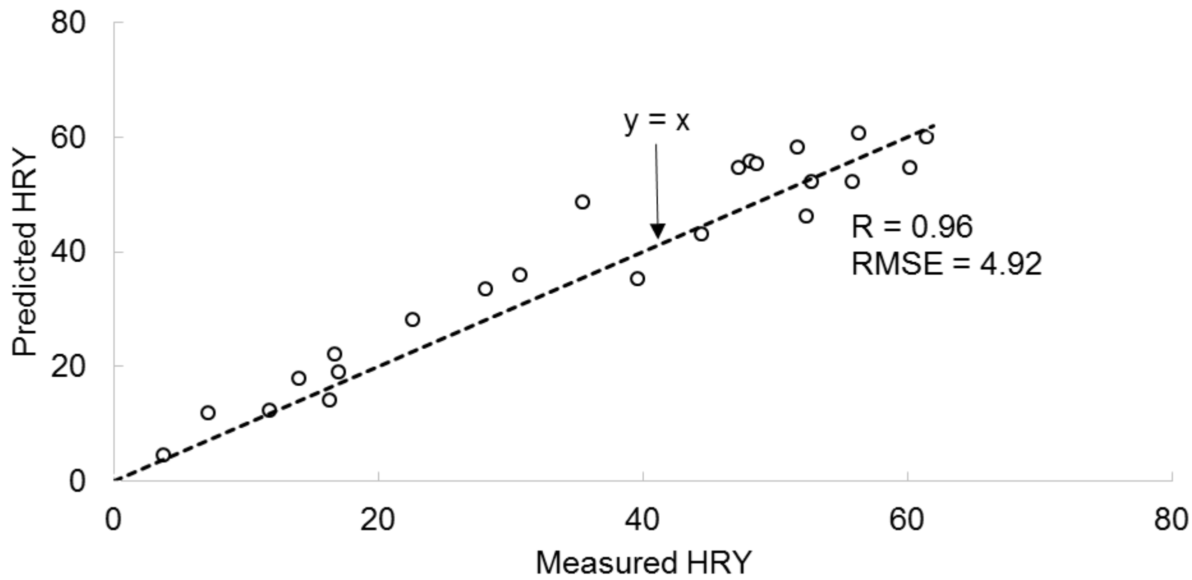

Figure 9. Head rice yield (HRY) predicted using equation 1 (y = 63.124 – 0.603x) vs HRY determined through laboratory milling for the 23 sub lots allocated as a validation set. R is the correlation coefficient and RMSE is the root mean square error.

E. Conclusions

Experiments were performed to evaluate the ability to observe fissures in rough rice kernels using an X-ray system. A 3X magnification provided a 33 × 50-mm field of view allowing 50 – 70 rough rice kernels to be observed per X-ray image. The 3X magnification was deemed sufficient to provide an optimal balance between image resolution for fissure detection and the available field of view. Placing rough rice kernels on the width side, which is the manner in which rice kernels typically orient due to kernel shape and density, was found to provide a better representation of fissures present in kernels than on the thickness side when using the X-ray system. There was an overall trend to detect more fissured kernels with the X-ray system in rough rice kernels than a grainscope in brown rice kernels, particularly when the fissured kernel percentages were greater than 20%. For fissured kernel percentages less than 20%, the X-ray system and the grainscope were similar.

Head rice yield was strongly correlated with the percentage of fissured rough rice kernels, as indicated by a correlation coefficient (R) of -0.97 and a coefficient of determination (R^2) of 0.95. The existence of such a strong correlation is a valuable consideration for designing instruments that can rapidly estimate HRY by evaluating the percentage of fissured rough rice kernels in a rice lot.

Validation of this correlation equation was conducted. The correlation equation overpredicted HRYs by an average of 5 percentage points; the difference between predicted HRYs and those determined through milling were attributed to factors other than fissured kernels, such as the presence of immature, chalky, and insect-damaged kernels, which are likely to break during milling, further reducing HRY than what fissured kernels alone would. However, the equation derived in this study is still deemed useful in providing rapid estimates of expected HRY without lengthy milling analyses.

This study has shown the ability of X-ray imaging to adequately detect fissures in rough rice kernels, the form in which rice is most often dried and stored. Such detection capabilities provide opportunities for in-situ rough rice drying research aimed at better understanding of kernel fissuring kinetics.

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III. RELATIVE IMPACT OF KERNEL THICKNESS AND MOISTURE CONTENT ON RICE FISSURING DURING DRYING

A. Abstract

Individual kernel thickness and moisture content (MC) vary within rice panicles. These variations affect the drying characteristics of rice kernels and consequently, the milling yield. This study utilized an X-ray system augmented with an in-situ rice drying apparatus that enabled fissure detection in rough rice kernels during drying and tempering. Rough rice kernels of two long-grain cultivars (Roy J and CL XL745), each at two MC levels (20% and 16%, w.b.), were fractionated into three thickness fractions (thin <1.98 mm, medium 1.98 - 2.03 mm, and thick >2.03 mm). Kernels from each of the 12 sub-lots were dried and tempered under controlled air conditions. Fissured kernel percentages (FKP) were determined from X-ray images taken during, before, and after drying and tempering. Kernel thickness and MC both affected moisture desorption fissuring. Generally, as kernel thickness increased, the FKP increased for high-MC lots. In regards to MC, high-MC lots were more prone to fissuring than the low-MC lots. Overall, these findings highlight the role of kernel properties on fissuring during drying.

B. Introduction

Fissures in rice kernels are fractures of the endosperm that can either be perpendicular to the long axis of the kernel (Kunze and Calderwood, 2004) or can be in an irregular alignment (Stermer 1968; Bautista et al., 2000). During milling, rice kernels tend to break at fissure sites, resulting in kernels that are classified as either head rice or brokens. Head rice represents kernels that are at least three-fourths of an intact kernel, while the remaining fragments are referred to as brokens (USDA, 2009). Brokens have a reduced commercial value, typically between 60% - 80% of the value of head rice (Siebenmorgen et al., 2008). Therefore, minimizing kernel fissuring is an important goal of the rice industry.

Research has shown that fissures can be incurred either pre-harvest or post-harvest. Pre-harvest fissures are usually due to rapid moisture adsorption by low-moisture content (MC) kernels (Kondo and Okamura, 1930; Kunze, 2008), whereas post-harvest fissures are mainly caused by improper drying and/or tempering (Kunze, 1978; Schluterman and Siebenmorgen, 2007). Kunze and Hall (1965) explained the mechanism of rice kernel fissuring due to moisture adsorption, proposing that the surface of the kernel expands when it adsorbs moisture hence experiencing compressive stress while the inner core incurs tensile stress. When the tensile stress exceeds the kernel tensile strength, fissuring initiates at the inner core and typically results in a transverse fissure. Cnosssen and Siebenmorgen (2000) presented a hypothesis that addresses rice kernel fissuring that occurs during drying and tempering. This hypothesis identifies the role of intra-kernel material state differences on fissure formation and has been applied in several drying studies (Schluterman and Siebenmorgen, 2004; Schluterman and Siebenmorgen, 2007; Ondier and Siebenmorgen, 2012).

The duration after drying when kernel fissuring becomes evident has been studied. Craufurd (1963) and Ban (1971) proposed that in rapid drying of rough rice, fissures do not develop until after drying had ceased. Similarly, Sharma and Kunze (1982) reported that fissures formed exclusively within 48 h after drying rice kernels at 60ºC for 2 h. Li et al. (1998) indicated that the fissured kernel percentage (FKP) increased rapidly during the initial 4 h after drying. Likewise, Siebenmorgen et al. (2005) showed that fissures visually appeared almost exclusively within the first 24 h after drying had been terminated and the fissuring process was completed within 48 h of drying termination.

Fissures in brown and milled rice kernels can be detected using video microscopes (Bautista et al., 2000), grainscopes (Cao et al., 2004; Siebenmorgen et al., 2005; Hayashi et al., 2015), and fissure inspection boxes (Iguaz et al., 2006; Bautista et al., 2009). However, these instruments are not applicable for fissure detection in rough rice kernels, the form in which rice is most often dried and stored. X-rays have the capability to penetrate hulls, thereby enabling fissure detection in rough rice kernels. X-ray imaging thus has great potential for providing a better understanding of rice fissuring kinetics.

Bulk rice lots usually contain kernels of various thicknesses, and thickness distributions can vary across locations, years, and harvest MCs (Bautista et al., 2007). Lu and Luh (1991) showed that during accumulation of starch in the rice endosperm, kernels first attain full length, then full width, and lastly full thickness; thus, within a single panicle, the most mature kernels are likely to be thicker than the least mature kernels.

Rice kernels of different thicknesses have been shown to have different degrees of fissuring susceptibility. Jindal and Siebenmorgen (1994) observed that thicker kernels were more susceptible to fissuring than thinner kernels when subjected to rapid moisture adsorption.

Similarly, Grigg and Siebenmorgen (2015) showed that the FKP of thickness-graded rice lots increased with increasing kernel thickness, a concept corroborated by Siebenmorgen et al. (1998). Additionally, both milled rice yield (MRY) (Grigg and Siebenmorgen, 2013) and HRY (Sun and Siebenmorgen, 1993) were shown to improve when thin (<2.00 mm) kernels were removed from bulk lots prior to milling; an indication that thinner kernels tend to have a weaker structural integrity than the thicker, bolder kernels.

In addition to thickness variation within rice panicles, the asynchronous kernel maturation process also produces inter- kernel MC variation within panicles. Chau and Kunze (1982) reported that the most mature kernels are at the top of the panicle and the least mature kernels at the bottom. These differences in maturation can cause individual kernel MCs within a panicle to vary by up to 10 percentage points (McDonald, 1976; Kocher et al., 1990; Bautista et al., 2009).

Previous research assessing the impacts of kernel thickness and/or MC on rice quality have mainly focused on milling operations. The fissuring susceptibility of rice kernels during the drying process has not been conclusively reported in terms of different kernel thicknesses and MCs. Using X-ray imaging, fissures can be detected in rough rice kernels, thus enabling quantification of fissures before, during, and after drying. The objective of this study was to determine the role of kernel thickness, MC, and the interaction thereof, on fissuring susceptibility of rough rice kernels.

C. Materials and Methods

Sample Procurement

Two long-grain rice cultivars, Roy J and CL XL745, were each harvested at two MCs from the University of Arkansas Northeast Research and Extension Center near Keiser, Arkansas. Roy J was harvested at 23.2% MC and then later from the same field at 19.0% MC, whereas CL XL745 was harvested at 23.5% MC and subsequently at 17.9% MC. The rice was cleaned using a dockage tester (XT4, Carter-Day Co, Minneapolis, Minn.) to remove material other than grain. During the cleaning and handling processes, some drying occurred, such that the two high-MC lots were measured to be approximately 20% and the two low-MC lots to be approximately 16% using a moisture meter (AM5200, Perten Instruments, Hägersten, Sweden). The lots were stored in a walk-in cooler at 4°C until experiments were conducted.

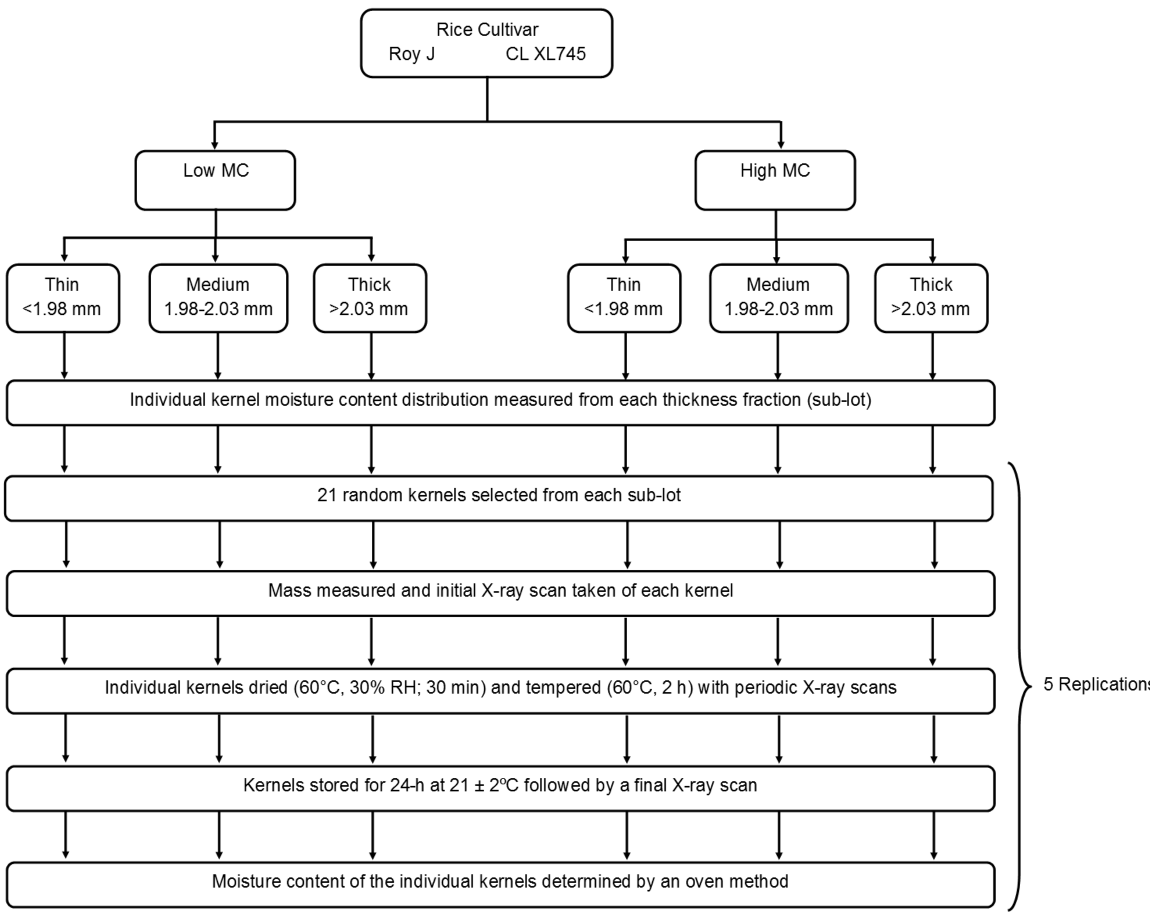

Figure 1. Flow diagram and experimental layout of the study.

Thickness Grading

From each of the four rice lots (2 cultivars × 2 MCs), 1 kg of rough rice was graded into three thickness fractions using a precision sizer (Model ABF2, Carter-Day, Minneapolis, Minn.) equipped with rotary screens (30-cm diameter) with 30-mm long slots of either 1.98- or 2.03-mm width. For each screening, the precision sizer was operated at 90 rpm for 4 min (Grigg and Siebenmorgen, 2015) using the 2.03-mm screen first, which retained the thick kernels, followed by the 1.98-mm screen, which retained the medium-thickness kernels. The resulting thickness fractions comprised thin (<1.98 mm), medium (1.98 mm << 2.03 mm), and thick (> 2.03 mm) kernel sub-lots. Individual kernel MCs of 100 kernels from each sub-lot were measured using a single kernel moisture meter (CTR-500E, Shizuoka Seiki Co., Ltd., Tokyo, Japan). The experimental layout is shown as part of figure 1. The resulting 12 sub-lots were then placed in the walk-in cooler at 4°C until drying.

Experimental Setup

The experimental setup comprised an environmental chamber (ESL 4CA Platinous, Espec, Hudsonville, Mich.), capable of automatically maintaining temperature in the range of -35°C to 150°C (±0.5°C) and relative humidity (RH) in the range of 6% to 98% (±1%), that provided conditioned air for drying. The conditioned air was suctioned from the chamber using a fan (3566 GPH, Sunlight Supply, Inc. Vancouver, Wash.), then passed through an in-line heater (AHP-7561, Omega Engineering, Inc. Stamford, Conn.) that was controlled with a voltage regulator (3PN1010B, Staco Energy Products Co., Miamisburg, Ohio) to augment the environmental chamber in maintaining the desired drying air temperature. The conditioned air was ducted into an X-ray system (UltraFocus 60, Faxitron Bioptics LLC., Tucson, Ariz.) within which a rice drying apparatus (figure 2) was positioned. The drying apparatus was equipped with a data sensor (Hobo Pro V2 U23-002, Onset Computer Corporation, Bourne, Mass.) to measure and record air temperature and RH during the drying and tempering experiments.

The rice drying apparatus, constructed using an acrylic material and polyethylene ducts, was used for positioning rough rice kernels inside the X-ray system for imaging while being dried and then tempered. The apparatus comprises two compartments, the interior compartment measuring 88.9 × 50.8 × 25.4 mm and the exterior compartment 254.0 × 152.4 × 38.1 mm. During drying, air from the environmental chamber was ducted through the interior compartment, which contained rough rice kernels. After a desired drying duration, the two three-way valves were turned to allow air from the environmental chamber to circulate through the exterior compartment, which maintained the interior compartment at a desired temperature, thus simulating post-drying tempering.

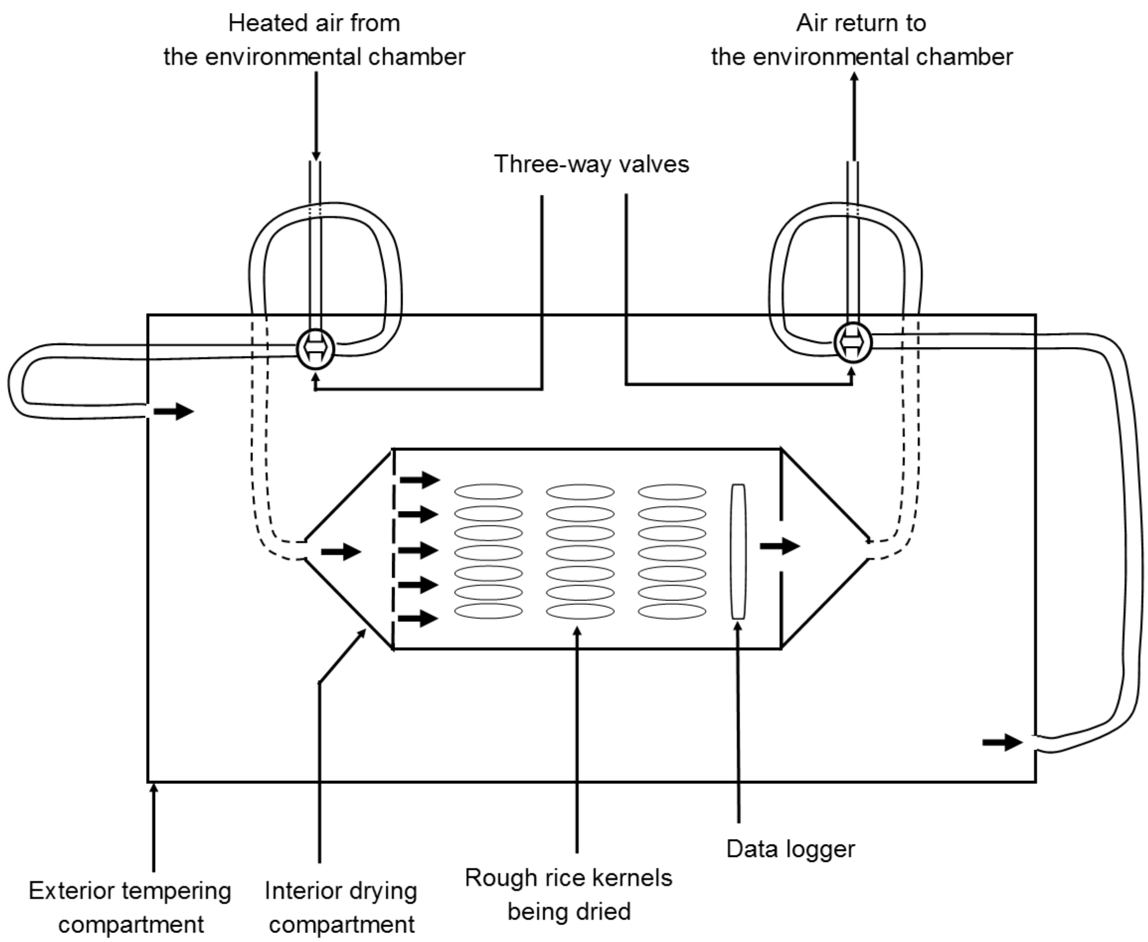

Figure 2. Schematic of the rice drying apparatus, designed to allow drying and tempering studies to be conducted within the X-ray system.

Experimental Layout

The experimental procedure is shown in figure 1. Prior to drying experiments, rice samples from each sub-lot were taken out of the walk-in cooler and allowed to equilibrate at 21 ± 2ºC. Thereafter, a 21-kernel sample was randomly selected from one of the 12 sub-lots to be used for a drying run, and the individual kernel mass for each of the 21 kernels was measured using a precision analytical balance (AB204-S, Mettler-Toledo LLC., Columbus, Ohio). The 21 kernels were then placed in the drying apparatus with each kernel secured in place on an acrylic plate using a 2-mm wide, double-sided adhesive tape (Double-sided adhesive, 3M Global

Gateway, Maplewood, Minn.). The drying apparatus was then positioned within the X-ray system at 4X magnification. This magnification was greater than the 3X magnification proposed in a previous study (Odek et al, in press) in order to compensate for the reduction in image resolution caused by the addition of the augmented apparatus. In using the 4X magnification, the field of view of the X-ray system was limited to 25 mm × 37.5 mm, which allowed for 21 kernels to be simultaneously observed at any given time. An initial X-ray scan was performed to identify initially-fissured, broken, and deformed kernels; only non-fissured, intact, and non-deformed kernels were monitored and included in the subsequent drying and FKP calculations. The 21-kernel sample was then dried using heated air at 60°C, 30% RH for 30 min and then tempered at 60°C for 2 h. Following drying and tempering, the acrylic plate along with the kernels secured, was placed in a ziplock bag for 24 h at room temperature (21 ± 2°C). A 24-h, post-drying storage duration is known to be the duration within which most fissures visually appear after drying (Siebenmorgen et al., 2005). A final X-ray scan was thus performed immediately after the 24-h storage duration had elapsed. The mass of each kernel was then measured and each kernel dried at 130°C for 24 h in a convection oven (Model 1370FM, Sheldon Mfg. Inc., Cornelius, Ore.). The final kernel MC, along with the initial and final kernel mass, were used to determine the kernel MCs before drying, as was used by Banaszek and Siebenmorgen (1993). The 21-kernel drying, tempering, and fissure detection procedure was replicated five times for each of the 12 sub-lots, thus generating 60 experimental units.

Enumeration of fissured kernels was performed by visually inspecting the X-ray images from each drying experiment. Fissured kernel percentage (FKP), defined as the number percentage of kernels that fissured due to the drying process, was calculated as the number of kernels with visible fissures after the drying process as a percentage of the initially non-fissured, intact, and non-deformed kernels. For this study, the initial MC of each individual kernel dried was determined but the thicknesses were only known to be within one of the three rough rice thickness fractions.

Statistical Analysis

The least square (LS) means of the FKPs due to the effects of kernel thickness and MC were compared using Tukey's Honestly Significant Difference procedure and Student's t-test at $\alpha<0.05$ using a statistical package (JMP Pro release 12.0.1, SAS Institute Inc., Cary, NC) to determine significant differences.

D. Results and Discussion

Mass and Moisture Content Characteristics of Rice Sub-lots

Table 1 shows the mass and MC characteristics of the thickness-fractionated sub-lots. For all lots, the thick-fraction sub-lot (>2.03 mm) comprised the greatest proportion of the lot mass. There was a moderate trend showing thin-fraction sub-lots to have slightly greater MCs than that of the medium- and thick-fraction sub-lots, particularly so for CL XL745, thus corroborating the studies by Lu et al. (1995) and Siebenmorgen et al. (1997) that showed most high-MC kernels tend to be thin and immature. The individual kernel MC standard deviations of the sub-lots indicated that the thin-fraction sub-lots had the greatest standard deviations, whereas the medium-fraction sub-lots had the least. This trend in turn indicate that inter-kernel MC uniformity was greater in the medium-fraction sub-lots than the thin- and thick-fraction sub-lots.

Table 1. Characteristics of Roy J and CL XL745 rough rice lots at two initial moisture contents each fractionated into three thickness fraction sub-lots.

Cultivar	**Lot moisture content (%w.b)**	**Thickness fraction (mm)**	**Mass retained (%)**	**Sub-lot MC (%w.b)**	**Individual kernel MC standard deviation (Percentage points)**
Roy J	16	<1.98	33.8	16.9	0.98
		1.98<<2.03	27.5	16.7	0.70
		>2.03	38.7	16.9	0.70
	20	<1.98	30.5	20.1	1.43
		1.98<<2.03	24.7	19.9	0.92
		>2.03	44.8	20.1	0.96
CL XL745	16	<1.98	26.1	16.7	0.91
		1.98<<2.03	34.3	16.0	0.64
		>2.03	39.6	16.1	0.74
	20	<1.98	16.9	19.9	1.44
		1.98<<2.03	22.7	19.1	0.92
		>2.03	60.4	19.2	1.00

Individual Kernel Moisture Content Distributions

Figure 3 shows individual kernel MC frequency distributions of the 12 rice sub-lots. There is a general trend showing a multi-modal distribution for the thin-fraction sub-lots, corroborating the greater standard deviation values of the thin kernels given in table 1. Additionally, most of the high-MC kernels in a rice lot tended to be within the thin-kernel fraction, corroborating observations by Wadsworth et al. (1982) and Lu et al. (1995).

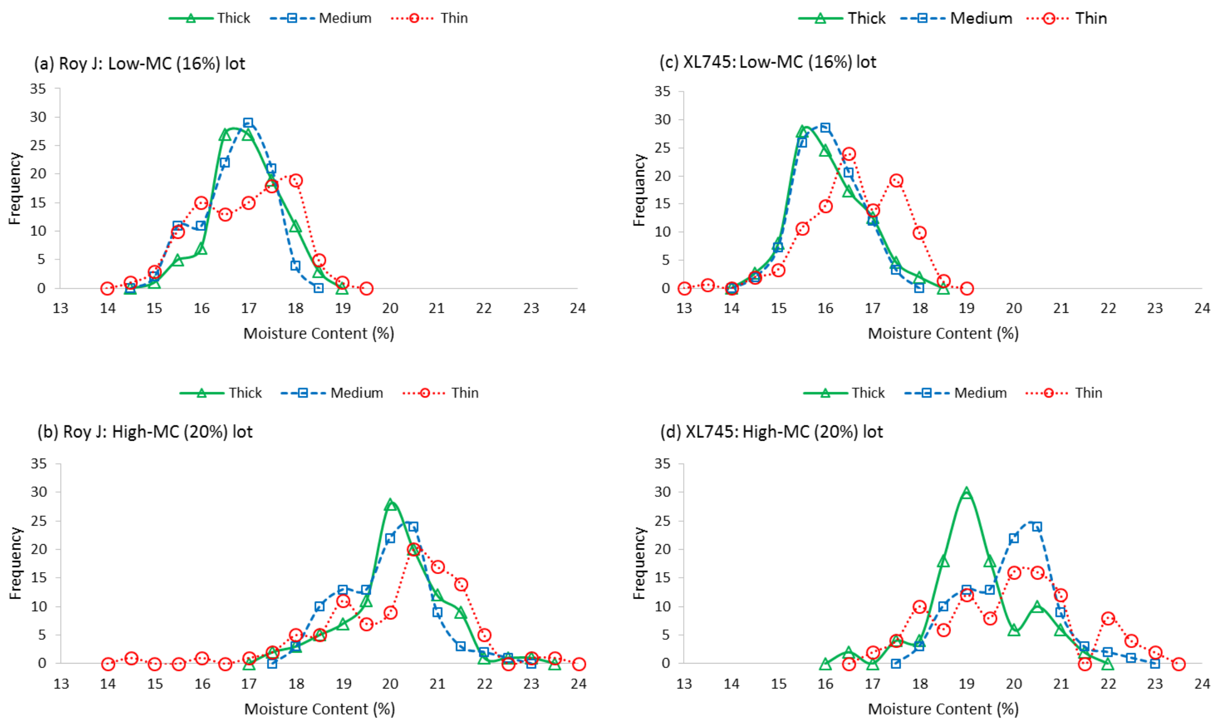

Figure 3. Individual kernel moisture content frequency distributions of thin (<1.98 mm), medium (1.98<<2.03 mm), and thick (>2.03 mm) kernel sub-lots of Roy J (a and b) and CL XL745 (c and d) rice cultivars, each at a low (≈16%) and a high (≈20%) bulk moisture content.

<u>Overall Impact of Moisture Content on Fissure Formation</u>

To illustrate the overall impact of MC on the FKP of rice lots at low- and high-MC, the weighted mass averages of FKPs from the three sub-lot thickness fractions of each cultivar/MC lot were calculated. Figure 4 displays these FKPs; a significantly greater percentage of kernels from the high-MC lots fissured as compared to kernels from the low-MC lots for both Roy J and CL XL745 cultivars.

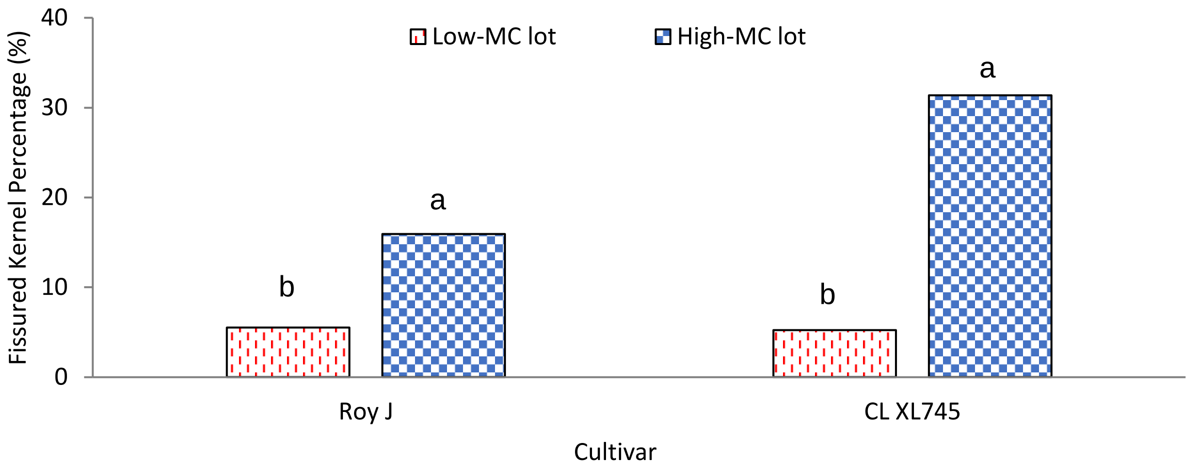

Figure 4. Effect of initial moisture content (MC) on rough rice fissured kernel percentage (FKP) after drying (60°C, 30% RH; 30 min), tempering (60°C, 2 h), and storing (24 h) each of the 12 thickness-fraction sub lots. Each bar represents the weighted average of the FKPs of the three sub-lot thickness fractions from each cultivar/MC lot. At the start of drying, each sub-lot was at either a low (≈16%) or a high (≈20%) initial MC. Values followed by the same letter within each cultivar are not significantly different (P>0.05).

Cnossen and Siebenmorgen (2000) proposed the use of material state properties, particularly those involving glass transition to explain kernel fissuring that occurs during the drying process. Figure 5 shows paths that high-MC kernels (a) and low-MC kernels (b) would hypothetical follow during drying. As indicated by these paths, high-MC kernels are more likely to transition from a glassy to a rubbery state during the drying process. If, during prolonged drying, sufficient portions of the kernel periphery of these high-MC kernels then transition back to the glassy state (figure 5a), intra-kernel material state differences could be created that could possibly lead to fissure initiation (Schluterman and Siebenmorgen, 2007). Most low-MC kernels, on the other hand, are likely to have remained in a glassy state throughout the drying process (figure 5b), thus intra-kernel material state differences would not be experienced by those kernels (Yang et al., 2003; Schluterman and Siebenmorgen, 2007) and fissuring would not be as likely to occur. As such, more kernels within the high-MC lots are reasoned to have fissured due to drying than those in the low-MC lots, thus leading to the trends shown in figure 4; these trends corroborate findings by Milner and Shellenberger (1953) in wheat kernels.

Following the above explanation, during drying, low-MC lot kernels are expected to remain non-fissured whereas high-MC lot kernels are expected to fissure. However, due to the individual kernel MC distributions shown in figure 3, some high-MC kernels within the low-MC lots fissured thus increasing the FKPs of the low-MC lots (figure 4), whereas some low-MC kernels within the high-MC lots did not fissure.

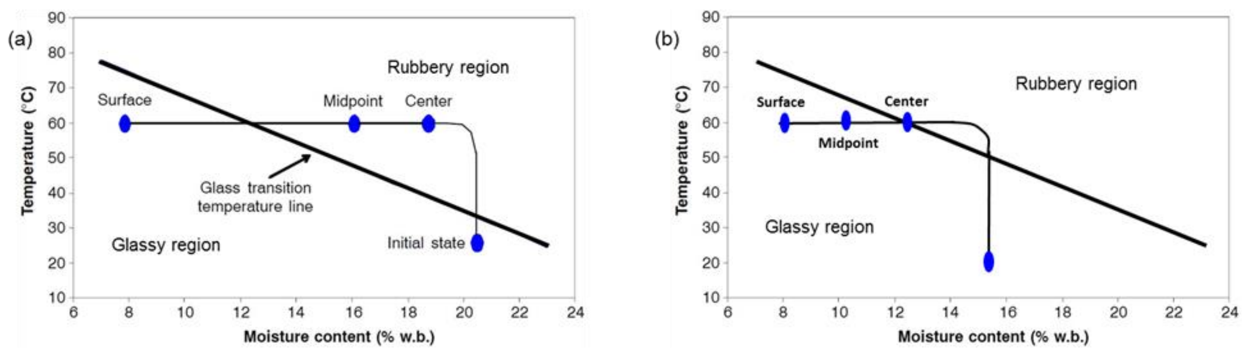

Figure 5. Hypothetical drying path of a high-MC (a) and a low-MC (b) rice kernel during high-temperature drying. Adopted from Schluterman and Siebenmorgen (2007).

Interactive Impact of Moisture Content and Kernel Thickness on Fissure Formation

Figure 6 shows the interactive effects between kernel thickness and MC on rice kernel fissuring due to the drying procedure of figure 1. Within the high-MC sub-lots of each cultivar, as kernel thickness increased, the FKP increased, although for Roy J, the apparent trend of increased FKP as kernel thickness increased was not significantly different across thickness fractions. The trend of increased FKP with increased kernel thickness did not exist for the low-MC sub-lots of both cultivars, as there were no significant differences in FKPs across thickness fractions for these sub-lots. This lack of trend for the low-MC sub-lots could have been associated with the overall low levels of fissuring that took place in the low-MC sub-lots, due to the glass transition impacts described previously.

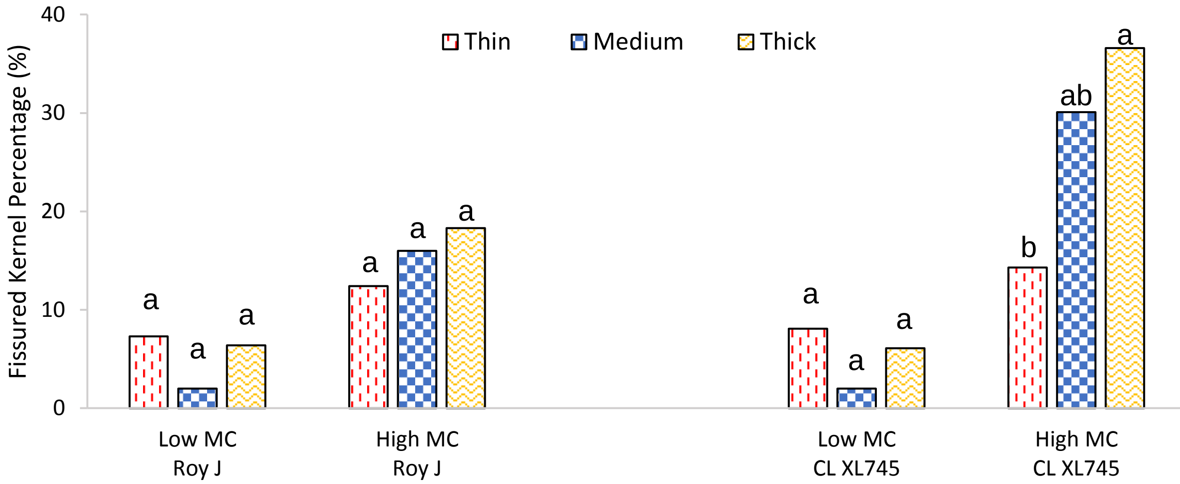

Figure 6. Kernel thickness and moisture content interactive effects on fissured kernel percentage after drying (60°C, 30% RH; 30 min), tempering (60°C, 2 h), and storing (24 h) 21-kernel sets of rough rice from each cultivar/moisture content/thickness fraction sub-lot. Each bar represents the average of fissured kernel percentage from five 21-kernel replications. At the start of drying, each sub-lot was either at a low (≈16%) or a high (≈20%) initial moisture content, and comprised a thin (<1.98 mm), medium (1.98<<2.03 mm), or thick (>2.03 mm) fraction. Values followed by the same letter within each cultivar lot are not significantly different (P>0.05).

Research has shown that kernels of various thicknesses have varying effects on resulting quality attributes (Wadsworth et al, 1979; Sun and Siebenmorgen, 1993; Chen and Siebenmorgen, 1997). Jindal and Siebenmorgen, (1994) showed the effects of kernel thickness on HRY reduction due to moisture adsorption. The study observed that thicker (>1.93 mm) kernels had greater HRY reductions than thinner (<1.78 mm) kernels when exposed to the same moisture adsorption conditions. However, such thickness trends on fissuring due to moisture desorption were not found in the literature. As earlier stated, when drying at 60°C, most low-MC kernels are reasoned to have have remained in the glassy region, below the rice glass transition line, and thus would not be expected to incur intra-kernel material state differences, which are known to contribute to rice kernel fissuring (Cnossen and Siebenmorgen, 2000). Therefore, the FKP trends due to thickness fractions were not apparent for the low-MC lots as shown in figure

6. This interactive effect between kernel thickness and MC on fissuring during drying shows the complexities involved in understanding and isolating the individual roles of kernel thickness and MC on fissuring. However, in general, when significant amounts of fissuring did occur, as kernel thickness increased, the FKP increased. It is hypothesized that during drying, the thicker kernels experienced greater intra-kernel, surface to core, MC and material state gradients than thinner kernels. Without apparent knowledge of state gradient formation within kernels, Arora et al. (1973) stated that MC gradients within rice kernels during drying contributed to fissure formation, thus thicker kernels are reasoned to be more susceptible to fissuring than thinner kernels.

E. Conclusions

Kernels from high-MC lots had significantly greater FKPs than kernels from the low-MC lots for both Roy J and CL XL745 cultivars. An interactive effect between kernel thickness and MC on fissuring during drying showed that the thick-fraction kernels of high-MC lots had greater FKPs than medium- and thin-fraction kernels for both cultivars, significantly so for CL XL745, with a trend of increased FKP with increased kernel thickness.

This study identified the impact of MC on fissuring susceptibility of rice kernels during drying, thus supporting the application of glass transition principles in minimizing kernel fissuring during drying. Additionally, the relative contribution of rice kernel thickness to fissuring was identified, thus reinforcing conclusions from previous studies that have proposed thickness grading of rice lots as a means to improving milling yields. Some complexities involved in understanding the individual roles of kernel thickness and MC on fissuring were highlighted.

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IV. CONCLUSIONS

This study evaluated an X-ray system as a method of fissure detection in rough rice kernels. Fissures were created by exposing kernels to various drying and post-drying treatment combinations that are known to result in a broad range of fissuring degrees and head rice yields (HRYs). Fissured kernel percentages (FKPs) were determined using the X-ray system in rough rice and brown rice, and compared to those detected by a grainscope in brown rice. Additionally, a correlation between HRY and FKP was established. Further, the X-ray system was augmented with a drying apparatus, together referred to as a drying system, which enabled fissure detection in rough rice kernels during drying. The drying system was then used to determining the relative impact of intrinsic kernel properties, specifically thickness and moisture content (MC), on fissuring during drying.

Magnification levels greater than 2X provided high-resolution images that allowed fissures to be detected in rough rice kernels. A 3X magnification level provided a 33 × 50-mm field of view that allowed approximately 50 – 70 rough rice kernels to be simultaneously observed. Increasing the magnification further increased the image resolution at the expense of a reduced field of view. When using the drying apparatus, the 4X magnification level used provided a 25 × 37.5-mm field of view that allowed for 21 kernels to be simultaneously observed.

Even with hulls intact, the X-ray system detected more fissured rough rice kernels than a grainscope did in brown rice, resulting in a strong, inverse and linear relationship between HRY and the FKP, with $R^2 = 0.95$. Such a correlation yielded an equation that could be considered in designing instruments that may estimate HRY by evaluating the FKP of a sample. This correlation confirmed the impact of kernel fissuring on milling yields, and the importance of a need to understand and minimize rice kernel fissuring.

The drying system comprising the X-ray system and the drying apparatus was used to conduct in-situ rice drying experiments that showed kernel thickness to have a significant impact on fissures formed during drying of high-MC lot kernels. For kernels at a high MC, FKPs increased with increased kernel thickness. For the low-MC kernels, there were no significant differences within thickness fractions. Moisture content was also shown to have an impact on FKP during drying. High-MC kernels had greater FKPs than low-MC kernels, a trend that was explained in part using the principles of the glass transition hypothesis.

This study forms a basis for further research aimed at providing a deeper understanding of rice fissuring kinetics, which may provide better rice drying procedures that could minimize milling yield reductions that are caused by kernel fissuring.