Individual Rice Kernel Drying Curves

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Abstract. *Drying data for individual rice kernels and bulk samples selected from various tillers of a plant and from different maturity groups were experimentally obtained. The data showed that over 93% of the drying occurred within 24 h of exposure to air at 40° C and 60% relative humidity. Differences in the equilibrium moisture content and drying rate constant among kernels were observed. Equilibrium moisture content was determined to be a function of kernel width, and the drying constant was found to be a function of initial moisture content and the ratio of kernel width to thickness.* ***Keywords.*** *Rice, Drying, Equilibrium, Moisture.*

Large variations in the moisture content (MC) of individual rice kernels have been measured during maturation and in bulk samples. It has been postulated that these variations may be the result of differences in the physical and/or hygroscopic characteristics among rice kernels that could affect kernel drying rates and equilibrium moisture contents (EMCs). Separation of kernels prior to drying, according to the characteristics that affect drying rates and EMCs, could lead to improved drying methods.

Literature Review

Researchers have measured differences in MC of individual rice kernels on a plant, among plants, and in equilibrated bulk samples. Kocher et al. (1990) conducted tests in which the MC variation among kernels on a plant was determined at several harvest dates for the 'Katy' variety. Kernel MC frequency distributions on early harvest dates were shown to be tri-modal in shape and indicated a range of kernel MCs from 10 to 37%* with a mean MC of 24%. The final harvest date showed a single mode with a range of kernel MCs from 9 to 25% and a mean MC of 15%. These results extend and support earlier work by Desikachar et al. (1973), Miller (1979), and Chau and Kunze (1982).

Siebenmorgen et al. (1990) measured MCs of individual kernels from equilibrated bulk samples of rough rice. Their results indicated that the standard deviation of the kernel MCs increased exponentially from approximately 0.5% at 10% average MC to 4.5% at 26% average MC. The coefficient of variation also increased with average MC, which indicated that the hygroscopic behavior of individual kernels in a sample was not the same as MC changed. The trends in standard deviation were similar to those presented by Nelson and Lawrence (1988) for corn.

Banaszek and Siebenmorgen (1990) showed that the MC in bulk samples of rough rice at initial moisture contents (IMCs) from 9 to 15% did not reach a common, asymptotic EMC when exposed to adsorptive conditions. A difference of one percentage point in EMC was measured when rough rice at sample IMCs of 9 and 15% were exposed to air at 30° C and 90% relative humidity (RH). The cause of varying hygroscopic behavior was hypothesized to be due to irreversible changes that may have occurred when the rough rice was dried to the various IMC levels, which resulted in the rice at each IMC level acting as a different material with each having a unique EMC.

Extensive research has been conducted to develop thin-layer drying equations and to better understand the desorption phenomenon in cereal grains, oilseeds, and other food products. A commonly used drying equation, sometimes referred to as the Newton drying equation, was presented by Henderson and Perry (1976). This equation has been shown to adequately predict changes in MC of thin-layers of grain during drying (Jayas and Sokhansanj, 1986, 1988; Pabis, 1982; Bruce, 1985; Zdrojewski, 1982; Kaminski, 1979; Cenkowski et al., 1986). Conversely, some researchers (Otten et al., 1989; Kulasiri et al., 1989; Tang et al., 1989) have used a modification of the Newton drying equation that is commonly referred to as Page's equation (Page, 1949). This modification consisted of including an additional parameter to the Newton equation, resulting in better agreement with experimental data.

Since wide ranges in MC among rice kernels have been shown to exist both in the field and in equilibrated samples, it was hypothesized that thin-layer drying could be more thoroughly quantified by determining the drying characteristics of individual kernels. Thus, the overall objective of this study was to determine if differences in individual kernel drying characteristics existed and, if so,

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*Unless otherwise specified, all references to moisture content (MC) are on a wet basis.

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what factors affected these characteristics. The specific objectives were to:

- Obtain drying data for single, rough rice kernels selected from various parts of a rice plant and from different maturity groups.
- Determine the effects of kernel dimensions, maturity, initial weight and IMC on drying characteristics.

Materials and Methods

Sample Preparation

Two long-grain varieties, 'Alan' and 'Newbonnet', were used. The 'Alan' samples were collected from a single plant grown in a greenhouse at the Northeast Research and Extension Center, Keiser, Arkansas, during August 1990. Sample collection consisted of manually removing the panicle from the mainstem, primary, secondary, and tertiary tillers. The rice kernels were then removed from the panicles and immediately placed in double, zip-lock plastic bags and stored at 1° C.

Approximately 5 kg of 'Newbonnet' rice that was combine-harvested at approximately 26% MC from a commercial field during August of 1990 was also used. The rice was harvested at this MC to obtain kernels at high MCs and at various stages of maturity. These samples were also placed in double, zip-lock plastic bags and stored at 1° C.

Variables measured for both varieties were kernel dimensions (length, width, and thickness), initial kernel weight, and IMC. In addition, kernel origin of the 'Alan' rice (i.e., kernels from panicles originating from different tillers) was selected for possible correlation to drying rates. To determine whether or not kernel maturity affected drying rates, the 'Newbonnet' variety was categorized into two maturity groups: (1) kernels that were green in color (immature); and (2) kernels that were non-green, in color (mature). All kernels selected were non-blank in that they contained a hard endosperm.

Drying Apparatus

Kernels were dried by placing single kernels in screen trays in a conditioning chamber (fig. 1). The conditioning chamber was built to accommodate six, screened trays located in the path of an airstream. The sample trays were constructed of wire screen with length, width, and height dimensions of 4.2 × 3.2 × 1.2 cm, respectively. Attached to each screen tray was a wire mounting that allowed the trays to be suspended in the airstream. During a typical test, five of the trays held a single kernel while the sixth tray held a bulk sample consisting of 100 kernels. The sixth tray was not used if 100 kernels were not available. Air was supplied to a plenum by a RH and temperature control unit (Parameter Generation and Control 300 CFM Climate-Lab-AA). According to the manufacturer's specifications, this unit is capable of maintaining RH within ±0.5% and dry-bulb temperature within ±0.2° C. Conditioned air from the plenum was supplied to the conditioning chamber by a small fan. Air conditions inside the conditioning chamber were maintained at 40° C (dry-bulb) and 60% RH for all tests and were monitored with a digital thermometer and a dew point hygrometer. After the air passed through the conditioning chamber, it was returned to the control unit to form a closed loop system. The airflow rate through the conditioning chamber, as measured with a hot-wire anemometer, was 1.4 L/s. A more detailed description of the experimental system is given by Siebenmorgen et al. (1991).

The change in kernel weight during drying was monitored to determine the change in sample MC. A digital balance (Fisher Scientific, Model A-200DS) with a readability of 0.01 mg was used. A personal computer (PC) and robot arm performed all weighing operations during each test, allowing unattended sample weighings. The robot arm also allowed samples to be weighed consistently during each sampling time, which eliminated possible human error if a technician performed the tasks. At selected weighing times, the conditioning chamber door was opened with a modulator motor, and the robot arm picked up a sample tray from the chamber and placed it on the balance platform. After the balance stabilized, the weight was recorded through the use of the PC and the RS-232C serial port of the balance. The sample tray was then placed back into the conditioning chamber. This weighing process was repeated for the remainder of the sample trays. After the last sample tray was placed back into the conditioning chamber, the chamber door was closed. Approximately eight minutes were required to complete each weighing interval.

Test Procedure

At the start of each test, five kernels from one of the variety/kernel classification combinations (table 1) were selected. Since kernel length was highly variable in comparison to width and thickness, kernel selection was primarily based on length. To obtain kernels with a large range of lengths for each variety/kernel classification, several kernels were placed parallel to each other in order of decreasing length. The longest, shortest, and three additional kernels were selected for a given test. The

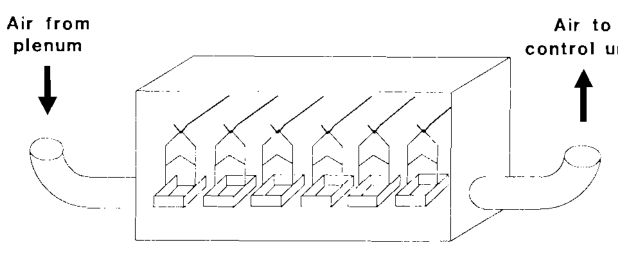

Figure 1–Conditioning chamber with tray locations and airflow directions.

Table 1. Number of samples tested for each variety and kernel classification

Variety	Kernel Classification	Number of Single* Kernel Samples	Number of Bulk† Samples Tested
'Alan'	Mainstem	10	1
	Primary	10	1
	Secondary	10	1
	Tertiary	10	0
'Newbonnet'	Non-green	10	2
	Green	10	2
	Mixed	--	2‡

* The numbers represent two test replications with five single kernel samples per test.
† Each bulk sample contained 100 kernels.
‡ Mixed bulk samples contained 50 green and 50 non-green kernels.

length, width, and thickness of each of the five kernels were measured with a micrometer to within 0.01 mm. Immediately after measuring the five single kernels, each kernel was placed in a small zip-lock bag to prevent moisture loss prior to conditioning. A bulk sample consisting of 100 kernels was selected randomly from the same variety/kernel classification combination as that of the five single kernels and immediately placed in a zip-lock plastic bag. Care was taken during selection to ensure that the kernels were not blank. Another criteria for kernel selection for the 'Newbonnet' variety, besides kernel length, was maturity as indicated by kernel color. The kernels for these tests were first classified as green in color (immature) or non-green in color (mature), and then the length selection procedure used with the 'Alan' variety was applied. All 'Alan' samples were non-green in color.

Each empty sample tray was weighed using the digital scale prior to the start of each test. A single kernel was randomly placed in each of the first five trays, and the 100 kernel bulk sample was placed in the sixth tray. The weights of the trays plus the respective samples were then determined. The tray and sample combinations were then placed in the conditioning chamber to begin drying. At time intervals of 1, 2, 3, 4, 6, 8, 16, 24, 48, 72, 96, and 120 h (some tests had an additional weighing interval of 144 h) from the start of drying, each sample was removed from the chamber using the robot arm and weighed. Immediately after the last weighing interval, the MC of each sample was determined by a whole-grain oven procedure for rough rice given by Jindal and Siebenmorgen (1987). Given the final MC of each sample, calculation of sample MCs at each weighing interval could be determined. Pertinent information regarding replications and total number of kernels tested for each variety/kernel classification combination is shown in table 1.

Results and Discussion

Drying Data

Individual kernel drying data for one of the two replications of each variety/kernel classification group listed in table 1 are shown in figures 2 and 3. In general, figures 2 and 3 show similar patterns in that most of the drying occurred within 24 h of exposure to the conditioned air. Figure 2, displaying the drying data for kernels from the mainstem, primary, secondary, and tertiary tillers of the 'Alan' variety, indicates that 94%, 99%, 98%, and 96%, respectively, of the drying occurred within 24 h of exposure.

The most notable difference in the drying data is that the primary and secondary kernel classification groups had higher IMCs than those of the mainstem kernels. The tertiary kernel group showed the highest IMCs. Kocher et al. (1990) stated that the rice plant produces tillers over a three-week interval, which leads to tillers at various stages of maturity and thus may explain the differences in IMC (or maturity) among the kernel classification groups.

Figure 3 displays drying data for the non-green and green kernels of the 'Newbonnet' variety. The non-green kernel drying data show trends that were similar to the 'Alan' variety. Within the 'Newbonnet' variety, the green kernels show IMCs which were higher than those of the non-green kernels. Thus, kernel color may be an indication

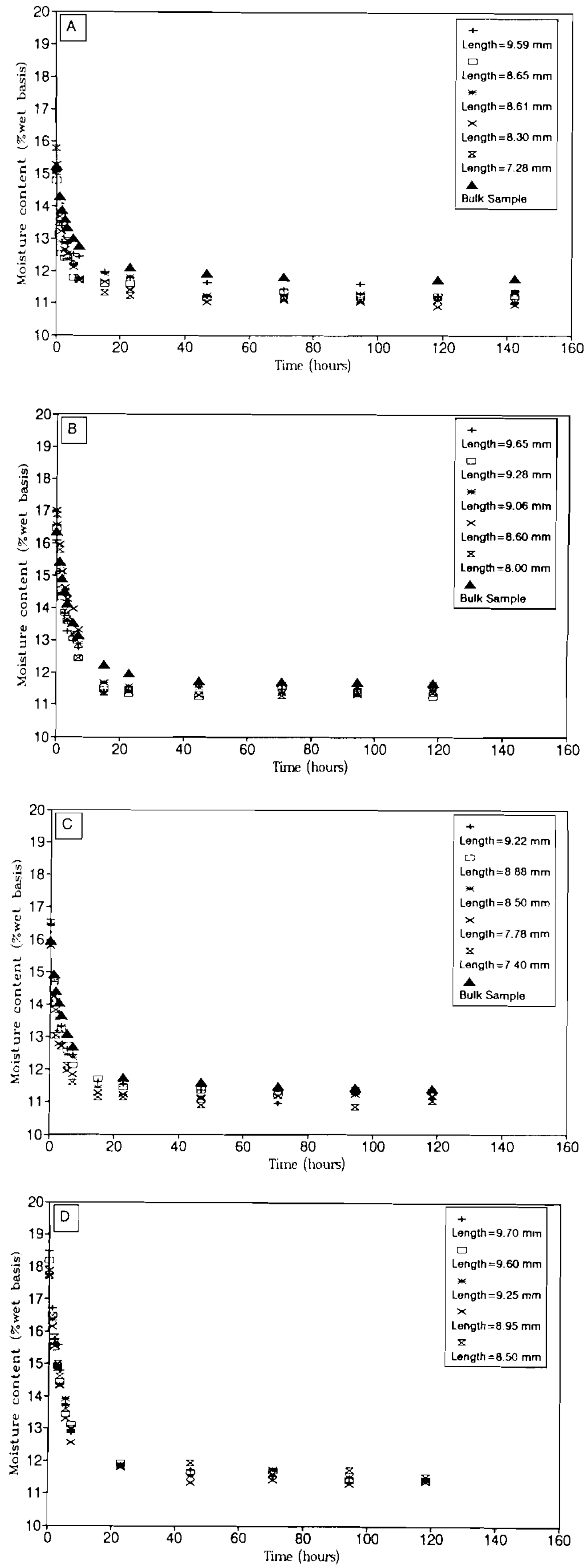

Figure 2–Drying date for long-grain rough rice kernels of various lengths for the mainstem (A), primary (B), secondary (C), and tertiary (D) kernels of the 'Alan' variety. Air condition was 40° C and 60% RH.

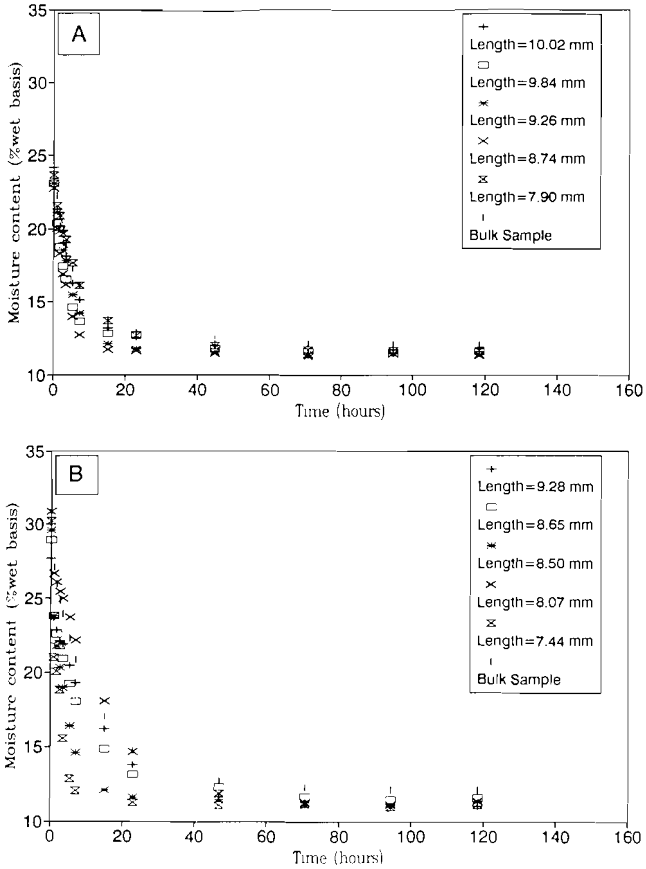

Figure 3–Drying data for long-grain rough rice kernels of various lengths for non-green (A) and green (B) kernels of the 'Newbonnet' variety. Air condition was 40° C and 60% RH.

of maturity. After 24 hours of exposure, over 95% and 93% of the total amount of drying had occurred in the non-green and green kernels, respectively.

Drying Equation

The MC data were analyzed using the following Newton drying equation (Henderson and Perry, 1976):

$$MR = \exp\left(-k*t\right) \quad (1)$$

where

- MR = (MC (t) − EMC) / (IMC − EMC) (moisture ratio, dimensionless)
- MC (t) = moisture content at time, t (% wet basis)
- EMC = equilibrium moisture content (% wet basis)
- IMC = initial moisture content (% wet basis)
- k = drying constant (h^{-1})
- t = time (h)

Equation 1 can be rearranged to better represent MC as a function of time:

$$MC\left(t\right) = \left(IMC - EMC\right)\exp\left(-k*t\right) + EMC \quad (2)$$

The NLIN least squares procedure from SAS (1987) was used to fit equation 2 to the MC data of each kernel and bulk sample. As such, this procedure was utilized as a method of statistically determining the asymptotic, EMC value, as well as the drying constant (k) for each kernel. Typically, a statistical test of comparisons between mean values is used to determine significant differences. However, since there were no mean values of EMC or k for each kernel or bulk sample, a comparison of means test could not be performed. Thus, to determine if the EMC and k values were different between kernels and bulk samples, the predicted parameter estimates (EMC and k) and corresponding 95% confidence interval of the estimates resulting from equation 2 for each kernel and bulk sample were plotted in figures 4 through 7.

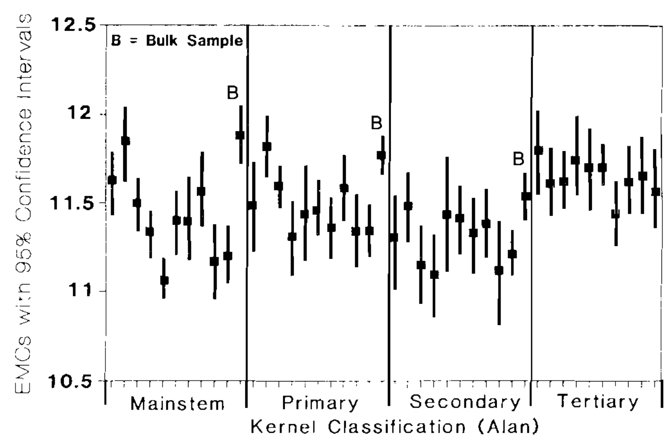

Figure 4–Predicted equilibrium moisture contents (squares) and 95% confidence intervals (bars) for long-grain rough rice kernels from the mainstem, primary, secondary, and tertiary tillers from a plant of the 'Alan' variety.

Figure 4 shows a range of asymptotic EMCs (11.1 to 11.8%) among samples of the 'Alan' variety. Most confidence intervals overlapped within the 'Alan' variety indicating similarity. However, there were several instances in which the confidence intervals did not overlap indicating EMC differences. There also appear to be differences in the range of confidence intervals between kernel classification groups. The mainstem group shows a wider range in confidence intervals than the tertiary group, which indicates that the kernel EMCs of the mainstem

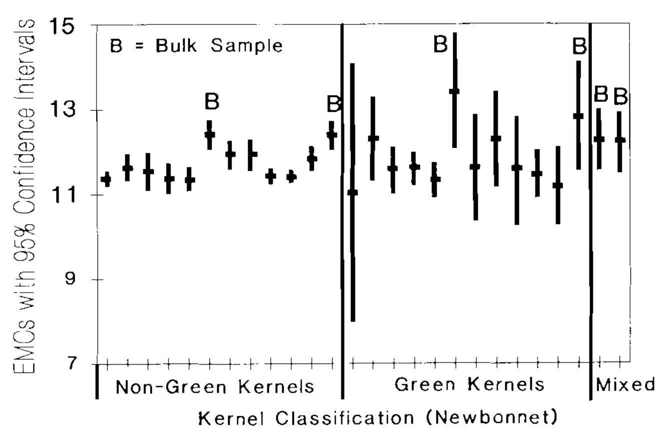

Figure 5–Predicted equilibrium moisture contents (squares) and 95% confidence intervals (bars) for long-grain rough rice kernels of the 'Newbonnet' variety.

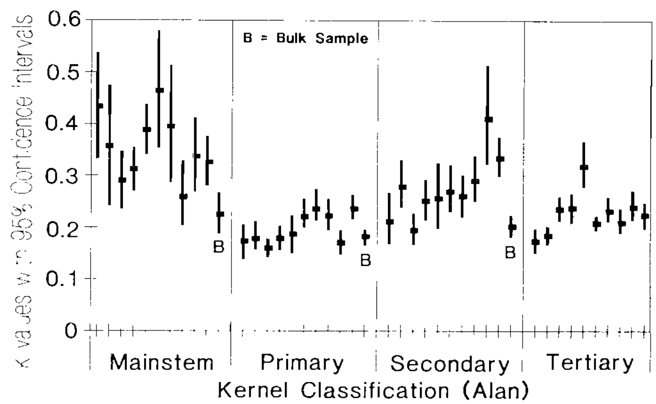

Figure 6–Predicted drying constants (k values) and 95% confidence intervals for long-grain rough rice kernels of the 'Alan' variety.

group vary more than the kernel EMCs of the tertiary group.

The bulk sample EMCs were higher than those of the single kernel samples. One possible explanation is that the airflow pattern around the kernels in the bulk samples was not the same as that of the single kernel samples. A second possible reason for the differences in EMCs between the single kernel samples and the bulk samples is the oven procedure used to determine the MC of the samples at the end of each test. Jindal and Siebenmorgen (1987) showed that oven temperature and drying time had significant effects on the apparent MC of a whole-kernel bulk sample. The oven procedure used by Jindal and Siebenmorgen consisted of drying 25-g samples of rough rice in an oven at 130° C for 24 h. The use of single kernels instead of 25-g samples may have led to errors in single kernel MC measurement, thus indicating lower EMCs and MCs with respect to time as compared to the bulk samples. A third possible explanation for differences between single kernel and bulk sample EMCs is that the structural and/or compositional constituents of the kernels comprising the two sample types (single kernel and bulk sample) were different.

Figure 5 shows a wide range of predicted EMCs (11.0 to 12.3%) among samples of the green and non-green kernel classification groups of the 'Newbonnet' variety. The EMC confidence intervals of the green kernel group were, for the most part, larger than those of the non-green kernels. The large EMC confidence interval for the first kernel in the green kernel group was attributed to an extremely high IMC (45%) of this kernel, which resulted in equilibrium not being reached within 120 h of exposure to the conditioned air. The drying data for this kernel belonged to the replication not shown in figure 3.

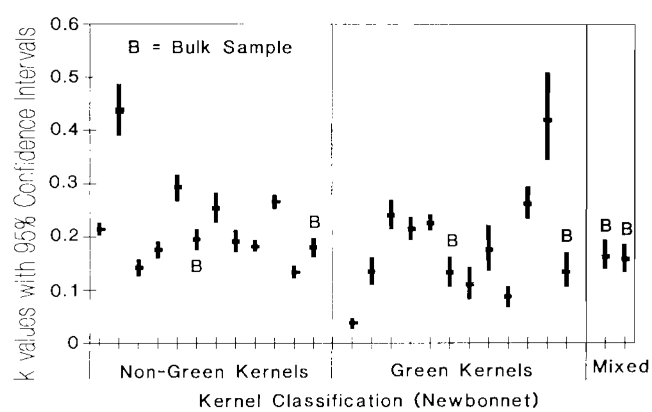

Figure 7–Predicted drying constants (k values) and 95% confidence intervals for long-grain rough rice kernels of the 'Newbonnet' variety.

The standard deviation of individual kernel EMCs among all 'Alan' kernels was 0.20% with an average EMC of 11.46%. The standard deviation of individual kernel EMCs among the 'Newbonnet' kernels was 0.32% with an average EMC of 11.59%. Siebenmorgen et al. (1990) reported a standard deviation of 0.37% at an average MC of 11.87% for rough rice. Thus, there appears to be a reasonably close comparison of kernel EMC standard deviations between studies.

The predicted drying constant (k) and corresponding 95% confidence intervals for the 'Alan' rice are displayed in figure 6. The intervals indicate that there were differences in k values within each kernel classification group; however, most differences occurred between the kernel classification groups. For instance, the predicted k values and confidence intervals of the mainstem group were, for the most part, higher than those of the primary and tertiary groups, which suggests that mainstem kernels dry at a faster rate than those of the primary and tertiary groups. Thus, if the mainstem kernels were the most mature as indicated by their lower IMCs, kernel maturity may play a role in kernel drying rates with the most mature kernels drying at a faster rate. The bulk sample drying constants were generally less than those of the single kernel samples, thus indicating faster drying rates of the single kernels than the bulk samples. This supports the earlier discussion regarding differences between individual kernel and bulk sample EMCs.

Figure 7 displays the predicted k values and corresponding confidence intervals for the 'Newbonnet' rice. The range in k values within each kernel classification group suggests that there were differences in drying rates from kernel to kernel within each classification group. There do not appear to be differences in k values between groups or between bulk samples and single kernel samples.

A t-test (Miller and Freund, 1985) was conducted on replications which contained a bulk sample to determine if the bulk sample EMC and k value for a given replication was significantly different from the mean EMC and k value of the single kernel samples from that replication. The t-test results indicated significant differences at the 5% level between the bulk sample EMC value and the mean EMC value of the single kernels samples for both the 'Alan' and 'Newbonnet' variety/kernel classification groups. Similar results were indicated for the k value of the 'Alan' classification groups; however, no significant differences were found between the bulk sample k value and the mean k value of the single kernel samples of the 'Newbonnet' classification groups.

Duncan's multiple range test (SAS, 1987) was used to determine if there were differences in the mean values of the drying constant (k) and the EMC across replications, varieties, and kernel classification groups. Since the primary focus of this study was to determine if the drying characteristics from kernel to kernel were different, the bulk sample data were not included in the Duncan tests.

Table 2. Duncan's multiple range test results on k and EMC values obtained using equation 2 with bulk sample data omitted from the analysis

Variety	Kernel Classification	k Value (Mean)*	EMC Value (Mean)*
'Alan'	Mainstem	0.3588 a	11.409 bc
	Primary	0.1996 c	11.472 b
	Secondary	0.2805 b	11.287 c
	Tertiary	0.2283 c	11.652 a
'Newbonnet'	Non-green	0.2297 d	11.580 d
	Green	0.1933 d	11.594 d

* Mean in columns followed by the same letters are not significantly different at a 5% level.

There were no significant differences of mean k or EMC values between replications at a significance level of 5%. There were significant differences in the mean k values between varieties; however, no significant differences were found in mean EMC values between varieties. The Duncan test results of comparing mean k and EMC values across kernel classification groups of a given variety are shown in table 2. Significant differences were found between the mean k and EMC values within the 'Alan' kernel classification groups, and no significant differences were found between the mean k and EMC values within the 'Newbonnet' kernel classification groups.

Development of a Relationship for the k and EMC Parameters

Since test results showed some differences in k and EMC values, the following kernel variables were investigated as being related to the k and EMC values:

- L1 = kernel length (mm)
- L2 = kernel width (mm)
- L3 = kernel thickness (mm)
- L1/L2 = kernel length to width ratio (dimensionless)
- L1/L3 = kernel length to thickness ratio (dimensionless)
- L2/L3 = kernel width to thickness ratio (dimensionless)
- L1(L2)L3 = product of kernel length, width and thickness (mm^3)
- IMC = initial kernel moisture content (% wet basis)
- WT = initial kernel weight (g)
- V = approximation of initial kernel volume (mm^3)
- SA = approximation of initial kernel surface area (mm^2)

Kernel volume and surface area were estimated using the following equations given by Wadsworth et al. (1979) and Stroshine et al. (1991), respectively:

$$V = 0.53\,(L1)\,(L2)\,(L3) - 6.68, \text{ and}$$

$$SA = 2\pi\,(L2/2)^2 + (2\pi/x)\,(L1/2)\,(L2/2)\sin^{-1}(x),$$
$$\text{where } x = (1 - ((L2/2)\,/\,(L1/2))^2)^{0.5}$$

The REG regression procedure (SAS, 1987) was used to correlate the k and EMC values of all samples to the above variables. The following are the resultant k and EMC equations:

Table 3. Drying equation 2 and pertinent regression coefficients and statistics

Equation 2: $MC(t) = (IMC - EMC)\exp(-k * t) + EMC$ MSE = 0.7597
where $EMC = a\,(L2) + b(L2^2)$
$k = c\,(IMC) + d(L2/L3)$

Coefficients	Standard Error of Estimates
a = 8.772171595	s (a) = 0.29632457073
b = – 1.626085841	s (b) = 0.12675676712
c = – 0.013261538	s (c) = 0.00029069493
d = 0.417326557	s (d) = 0.00833814093

$$EMC = a\,(L2) + b\,(L2^2) \tag{3}$$

$$k = c(IMC) + d(L2/L3) \tag{4}$$

Thus, kernel width (L2) was the only variable that was significant at a level of 5% for use in predicting EMC; whereas, IMC and L2/L3 were likewise significant in predicting k. On the assumption that kernel maturity is a function of IMC, it appears that the drying rate of single kernels is a function of kernel maturity due to the significance of IMC in equation 4.

Equations 3 and 4 were substituted into equation 2 and the NLIN procedure from SAS was used again to fit equation 2 to the entire pooled data set. The resulting error mean square (MSE) for equation 2 was 0.7597. Based on the relatively small MSE, the resulting prediction equation for single kernel drying is adequate for the scope of this study. The regression coefficients and pertinent regression statistics for equations 2 through 4 are presented in table 3.

Alternate Drying Equation

Page (1949) introduced the exponent "n" to the time variable in equation 1 to better predict thin-layer drying data for shelled corn:

$$MR = \exp(-k * t^n) \tag{5}$$

Due to the success of Page's equation in modeling sorption characteristics, equation 5 was analyzed for use in describing the MC data obtained in this study. The regression procedure used in determining the coefficients in equation 2 was applied again to equation 5. Duncan's multiple range test was used to determine if the mean value of the regression coefficients (i.e., k, EMC, and n) among replications, varieties, and kernel classification groups were significantly different. The Duncan test results for k and EMC values were similar to those described previously. In addition, no differences were found in the mean n values between replications or varieties; however, significant differences were found between the mean n values within the 'Alan' and 'Newbonnet' kernel classification groups.

The regression procedure used to develop equations 3 and 4 was used to develop equations predicting EMC, k, and n values resulting from the use of equation 5. After substitution of the resulting prediction equations into equation 5, the resulting MSE (0.6699) was slightly lower than that of equation 2; however, a total of ten terms were required in the EMC, k, and n equations, which was deemed excessive. A lower MSE (0.6523) resulted when

Table 4. Drying equation 5 and pertinent regression coefficients and statistics

Equation 5: $MC(t) = (IMC - EMC) \exp(-k * t^n) + EMC$ MSE = 0.6523

where $EMC = a(L2) + b(L2^2)$

$k = c(IMC) + d(L2/L3)$

Coefficients	Standard Error of Estimates
a = 8.931756455	s (a) = 0.27870105123
b = − 1.718004082	s (b) = 0.11933105283
c = − 0.015707958	s (c) = 0.00034446362
d = 0.513105211	s (d) = 0.00969017647
n = 0.788276520	(average value of all drying curves)

the forms of equations 3 and 4 were used in conjunction with an average n value of all drying curves. The resulting regression coefficients and pertinent regression statistics for equation 5 are presented in table 4.

The authors caution the use of equations 2 and 5 to conditions beyond those of the current study. If a single equation is to be used for predicting the drying behavior of individual kernels of rough rice, further research is needed to determine the effects that other variables (i.e., differences between plants, drying air temperature and RH, and other varieties) have on the drying characteristics of these single kernels.

Summary and Conclusions

Drying data for individual rice kernels and bulk samples of two long-grain varieties ('Alan' and 'Newbonnet') were measured. The 'Alan' kernels were selected from the mainstem, primary, secondary, and tertiary tillers of a plant. The 'Newbonnet' kernels, selected from a bulk sample, were classified as green or non-green in color. The data for all variety/kernel classification combinations showed that over 93% of the drying occurred within 24 h of exposure to air at 40° C and 60% RH.

The 'Newton' drying equation was used to statistically determine the asymptotic EMC and drying constant (k) for each kernel and bulk sample tested. Results indicated differences in EMC and the drying constant between kernels. The ranges of EMC between kernels for the 'Alan' and 'Newbonnet' varieties were 11.1 to 11.8% and 11.0 to 12.3%, respectively. Significant differences in the drying constant were found between varieties. No significant differences were found in the EMC between varieties. Significant differences in EMC and drying constant were shown to exist between kernels originating from different tillers of the 'Alan' variety. However, no significant differences in EMC or the drying constant were found between green and non-green kernels of the 'Newbonnet' variety. If an assumption is made that kernel color (green or non-green) is a strong indication of kernel maturity, then it appears that kernel maturity does not affect the drying behavior of rough rice. However, regression analysis showed that the drying constant was a function of IMC. On the assumption that kernel maturity is correlated to kernel MC at time of harvest, it appears that the drying rate of single kernels is a function of kernel maturity. Thus, based on conflicting results between representing kernel maturity by color or IMC, a definitive conclusion as to the relationship of kernel maturity to kernel drying behavior cannot be made.

Regression analysis using the Newton drying equation showed EMC to be a function of kernel width and the drying constant to be a function of IMC and the ratio of kernel width to thickness. Page's equation resulted in a slightly lower MSE value as compared to the Newton drying equation; however it also requires an additional parameter.

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Table 4. Drying equation 5 and pertinent regression coefficients and statistics

Equation 5: $MC(t) = (IMC - EMC) \exp(-k * t^n) + EMC$ MSE = 0.6523

where $EMC = a(L2) + b(L2^2)$

$k = c(IMC) + d(L2/L3)$

Coefficients	Standard Error of Estimates
a = 8.931756455	s (a) = 0.27870105123
b = − 1.718004082	s (b) = 0.11933105283
c = − 0.015707958	s (c) = 0.00034446362
d = 0.513105211	s (d) = 0.00969017647
n = 0.788276520	(average value of all drying curves)

the forms of equations 3 and 4 were used in conjunction with an average n value of all drying curves. The resulting regression coefficients and pertinent regression statistics for equation 5 are presented in table 4.

The authors caution the use of equations 2 and 5 to conditions beyond those of the current study. If a single equation is to be used for predicting the drying behavior of individual kernels of rough rice, further research is needed to determine the effects that other variables (i.e., differences between plants, drying air temperature and RH, and other varieties) have on the drying characteristics of these single kernels.

Summary and Conclusions

Drying data for individual rice kernels and bulk samples of two long-grain varieties ('Alan' and 'Newbonnet') were measured. The 'Alan' kernels were selected from the mainstem, primary, secondary, and tertiary tillers of a plant. The 'Newbonnet' kernels, selected from a bulk sample, were classified as green or non-green in color. The data for all variety/kernel classification combinations showed that over 93% of the drying occurred within 24 h of exposure to air at 40° C and 60% RH.

The 'Newton' drying equation was used to statistically determine the asymptotic EMC and drying constant (k) for each kernel and bulk sample tested. Results indicated differences in EMC and the drying constant between kernels. The ranges of EMC between kernels for the 'Alan' and 'Newbonnet' varieties were 11.1 to 11.8% and 11.0 to 12.3%, respectively. Significant differences in the drying constant were found between varieties. No significant differences were found in the EMC between varieties. Significant differences in EMC and drying constant were shown to exist between kernels originating from different tillers of the 'Alan' variety. However, no significant differences in EMC or the drying constant were found between green and non-green kernels of the 'Newbonnet' variety. If an assumption is made that kernel color (green or non-green) is a strong indication of kernel maturity, then it appears that kernel maturity does not affect the drying behavior of rough rice. However, regression analysis showed that the drying constant was a function of IMC. On the assumption that kernel maturity is correlated to kernel MC at time of harvest, it appears that the drying rate of single kernels is a function of kernel maturity. Thus, based on conflicting results between representing kernel maturity by color or IMC, a definitive conclusion as to the relationship of kernel maturity to kernel drying behavior cannot be made.

Regression analysis using the Newton drying equation showed EMC to be a function of kernel width and the drying constant to be a function of IMC and the ratio of kernel width to thickness. Page's equation resulted in a slightly lower MSE value as compared to the Newton drying equation; however it also requires an additional parameter.

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