Drying characteristics of forage sorghum stalks

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Forage sorghum has been identified as a potential source of biomass for heating by direct combustion. An important aspect of the production system is crop drying prior to storage or processing, such as pelletizing. In order to properly evaluate the effects of maceration or other similar treatments on the field drying of sorghum, a baseline of the drying characteristics of sorghum needs to be established. This was accomplished by drying samples of sorghum stalks in an Armfield UOP8 laboratory-scale tray dryer at an air temperature of 50°C and air velocity of 0.5 m/s. Stalks were cut into either 200 mm or 50 mm lengths. For some of the 200 mm lengths, the ends were sealed in paraffin wax to duplicate infinite cylinders so that the drying characteristics of the waxy skin could be determined separately from the cut ends.

The data was fit to several standard exponential type models, including a two-term Newton model, and a separation of variables model based on Fick's law. The length of the stalk and the sealing of the ends significantly affected the drying rate. Statistical indicators demonstrated that standard exponential models adequately capture the drying curves and are on par with the separation of variables model. The two-term Newton model and the separation of variables model provided a distinction between the axial and radial moisture migration. Using the separation of variables model, the effective diffusivity of sorghum stalks was determined to be 4.17 x 10^{-8} and 8.81 x 10^{-6} m^2/hr in the radial and axial directions, respectively. **Keywords:** Drying characteristics, sorghum, biomass crops, effective diffusivity, modelling.

Le sorgho fourrager a été identifié comme source potentielle de biomasse pour le chauffage par combustion directe. Un aspect important du système de production est le séchage des plants récoltés avant l'entreposage ou la transformation tel que la granulation. De manière à évaluer les effets de la macération ou autres traitements similaires sur le sorgho séché au champ, une référence sur les caractéristiques de séchage du sorgho doit être établie. Ceci a été réalisé en séchant des échantillons de tiges de sorgho dans un séchoir à plateau de laboratoire Armfield UOP8 à une température de 50°C et une vitesse d'air de 0.5 m/s. Les tiges étaient coupées en longueurs de 200 mm ou 50 mm. Pour quelques unes des longueurs de 200 mm, les bouts étaient scellés avec de la cire de paraffine pour reproduire des cylindres infinis et qu'ainsi les caractéristiques de séchage de la couche cireuse puissent être déterminées séparément des bouts coupés.

Les données étaient comparées à plusieurs types de modèles exponentiels standardisés, incluent un modèle Newton à deux variables et un modèle à séparation des variables basé sur la loi de Fick. Le taux de séchage était significativement affecté par la longueur des tiges et le scellage des bouts. Des indicateurs statistiques démontraient que les modèles exponentiels standardisés représentaient adéquatement les courbes de séchage et se comparent adéquatement au modèle de séparation des variables. Le modèle à deux variables de Newton et le modèle de séparation des variables fournissaient une distinction entre la migration axiale et radiale de l'humidité. En utilisant le modèle de séparation des variables, la diffusivité réelle des tiges de sorgho était évaluée à 4,17 x 10^{-8} et 8,81 x 10^{-6} m^2/h respectivement dans les directions radiale et axiale. **Mots clés:** caractéristiques de séchage, sorgho, cultures de biomasse, diffusivité réelle, modélisation.

INTRODUCTION

The current interest in the use of annual and perennial grasses as bioenergy crops to aid in the mitigation of greenhouse gas emissions from the combustion of fossil fuels is presenting significant opportunities for primary producers. However, as this is a starting industry, there are several technological hurdles that must be overcome. Although there is an abundance of knowledge in the production of forages as animal feed, the production of bioenergy crops has differing agronomic and production practices. A key in the production of bioenergy crops is to minimize the energy inputs, particularly those derived from fossil fuels, and to minimize the carbon footprint of the production cycle.

Although many of the proposed bioenergy crops are perennial grasses, there are opportunities for the use of annual crops. One of the major advantages of annual crops is the ability for the producer to quickly adapt a crop to capitalize on positive changes in the market prices of bioenergy crops. Many perennial crops can take 2-4 years to become fully established and the stands are in production for many years, in some cases up to 20 years for crops such as miscanthus or switchgrass.

An annual crop that has received significant interest as a source for bioenergy production is sorghum (Carpita and McCann 2008; Habyarimana et al. 2004). The high yielding dry biomass and water-use efficiency of sorghum are two attractive qualities that promote it to be a candidate for bioenergy production (Amaducci et al. 2000; Habyarimana et al. 2004; Marsalis et al. 2010). Sorghum can be used for ethanol production and for direct combustion.

Grain sorghum and sweet sorghum have been proposed for the production of ethanol (Wang et al. 2008). Wortmann et al. (2010) demonstrated that yields and CO_2 reductions of sweet sorghum are lower than corn and grain sorghum; however net energy ratios were higher. Forage sorghum has been investigated as a potential lignocellulosic feedstock for ethanol production (Manzanares et al. 2012).

Forage sorghum has been proposed as an alternative feed for lactating dairy cows as it has higher water-use efficiency than silage corn (Marsalis et al. 2010). Yield potential from hybrid forage sorghum and sorghum-sudangrass hybrids were performed by Venuto and Kindiger (2008) with dry matter yields averaging 27.1 Mg ha^{-1} for single late season harvest and 25.5 Mg ha^{-1} for a two-cut harvest system. Studies on the partitioning of the dry matter in sorghum measured stem dry matter to be 18.1 Mg ha^{-1} while leaf dry matter was 8.1 Mg ha^{-1} (Amaducci et al. 2000). Stem diameter can be affected by planting densities, with smaller stem diameters as the planting densities increase, causing potential lodging issues (Snider et al. 2012).

Forage sorghum can also be planted late in the season, if adverse weather conditions limit the ability to plant early season crops. Furthermore, forage sorghum can be used in multi-cut systems, allowing for multiple harvests in a single season. However, in multiple harvest systems, there is a requirement for crop drying prior to densification, typically baling, if the moisture content is high. Many of the perennial bioenergy crops are harvested either in the late fall or in the spring, partially to avoid this issue. Not only does this allow for the moisture content of the crops to decrease naturally, but it also permits nutrients to leach back into the soil. In general, the moisture content needs to be below 50% to be suitable for combustion (McKendry 2002). Moisture content in the range of 15% or lower is ideal. These moisture contents can be reached by over-wintering many crops; however, there is also a decrease in the total biomass yield. In order to use a multi-cut system for sorghum, it is necessary to field dry the summer harvests. Sorghum, due to the relatively large thickness of the stalks, may require other field processing, such as maceration, to enhance field drying and to achieve desirable low moisture contents for burning. In some areas, due to climatic conditions, ensiling sorghum is more suited than baling, as the stems do not dehydrate quickly when in windrows (Worley and Cundiff 1996; Lardy and Anderson 2009).

There is very little information available on the drying of forage sorghum in the literature. Rocateli (2010) studied the effect of conditioning on the field drying of sorghum, and determined that the moisture content could be reduced below 20% for higher roller pressures and small gap sizes for the rollers. For non-conditioned sorghum, and for sorghum that was not intensively conditioned, the moisture content remained above 20% after 14 days of drying. Rennie et al. (2011) also observed that sorghum did not sufficiently dry in natural field conditions. The results of Rocateli (2010), however, suggest that intensive conditioning may result in better drying rates and the use of macerators or similar equipment may allow for successful field drying of sorghum.

In order to properly evaluate the effects of maceration or other similar treatments, a baseline of the drying characteristics of the crops needs to be established. The objective of this work is to investigate the drying characteristics of sorghum stalks. The metric used to determine the drying characteristics and to compare between trials was the effective diffusivity in the axial and radial directions for sorghum stalks. Only the drying characteristics of the stalks were evaluated in this study, as the leaves tend to dry much quicker than the stalks.

MATERIALS AND METHODS

The plant material consisted of forage sorghum [*Sorghum bicolor* (L.) Moench 'Canadian Forage Sorghum Hybrid 30' (CFSH 30)]. The experimental site was located in Kemptville, Ontario (45°00′ N, 75°37′ W). Sorghum was planted using typical agronomic practices and recommended fertilizer rates. The crop was allowed to mature before samples were taken to determine their drying characteristics.

Sampling for drying kinetics

Samples were collected from the field by cutting the stalks about 200 mm from the ground. Samples were taken after the morning dew had evaporated and no apparent surface moisture remained. Stalks and leaves were separated at the ligule and the leaves discarded. The initial moisture content of the stalks was measured using a Sartorius MA50 moisture analyzer (Sartorius Corporation, Göttingen, Germany). The measurements were carried out at 105°C and the instrument had an accuracy of 0.2%.

Sample preparation

The stalks of sorghum were cut into lengths of either 50 mm or 200 mm using a sharp edged knife. Some of the 200 mm stalks were sealed by dipping the cut ends into melted paraffin wax. By sealing the ends, a comparison could be made between the moisture loss through the surface of the stalks and through the cut ends of the stalk. Some of the 200 mm stalks were cut in half longitudinally to minimize the effects of the waxy skin. Table 1 details the different treatments. Stalk diameters were measured using calipers.

Drying experiments

The prepared sorghum stalks were placed in an Armfield UOP8 laboratory-scale dryer (Armfield Limited, Ringwood, England) equipped with a balance to continuously monitor the weight of the sorghum over time. The readings for the weight of sorghum were taken every 15 min for approximately 22 hours. The air velocity in the dryer was 0.5 m/s and the inlet air temperature was set at 50°C. A higher temperature was used in the trials than

Table 1. Treatments for the sorghum stalks.

Test	Length (mm)	# Pieces	Treatment
1	200	20	None
2	50	80	None
3	200	20	Waxed Ends
4	200	20	Split Longitudinally

would be typically observed in field drying operations. The objective of this work was to determine the baseline drying characteristics such that different field operations, such as maceration and conditioning, could be compared on the drying of sorghum stalks. Therefore, to expedite the data collection, a higher temperature was used. Three replicates were performed for each treatment.

MATHEMATICAL MODELLING

Governing differential equation

There are several available models to predict the moisture content of an object that is being dried (Rossello et al. 1997). For the sorghum stalks, a finite cylinder can represent the geometry. For this case, the rate of change of the dry basis moisture content, W, of the commodity can be modelled using Fick's law:

$$\frac{\partial W}{\partial t} = \left[D_s\left(\frac{\partial^2 W}{\partial r^2} + \frac{1}{r}\frac{\partial W}{\partial r}\right) + D_e\left(\frac{\partial^2 W}{\partial z^2}\right)\right] \quad (1)$$

where D_s is the effective diffusivity on the side of the stalk, D_e is the effective diffusivity on the ends of the stalks, r is the radial coordinate and z is the longitudinal coordinate. There are three basic assumptions with this model: (i) the initial moisture content, W_i, is uniform throughout the product, (ii) there is no shrinkage, and (iii) the surface is in equilibrium with the surrounding air (Rossello et al. 1997).

The solution of Eq. 1 can be obtained by using the method of separation of variables such that a series solution can be developed for the radial direction, modeled as an infinite cylinder, and the longitudinal direction, modeled as an infinite slab. The product of these two solutions will result in a solution for a finite cylinder. Thus, the moisture ratio at any given time, ψ_t, can be expressed as (Rossello et al. 1997):

$$\Psi_t = \left(\frac{W_t - W_e}{W_i - W_e}\right) = \Psi_r \Psi_z \quad (2)$$

The series solutions of ψ_r and ψ_z are (Rossello et al. 1997; Dandamrongrak et al. 2002; Senadeera et al. 2003):

$$\Psi_r = \sum_{i=1}^{\infty} \frac{4}{(\beta_i)^2} e^{-\left(\frac{\beta_i^2}{R^2} D_s\right)t} \quad (3)$$

$$\Psi_z = \sum_{i=1}^{\infty} \frac{2}{\left(i-\frac{1}{2}\right)^2 \pi^2} e^{-\left(\frac{\left(i-\frac{1}{2}\right)^2 \pi^2}{Z^2} D_e\right)t} \quad (4)$$

where β_i are the roots of the Bessel function. Taking only the first terms of Eqs. 3 and 4 yields the following expression for the moisture ratio at any given time:

$$\Psi_t = 0.561 e^{-\left(\frac{5.783}{R^2} D_s + \frac{\pi^2}{Z^2} D_e\right)t} \quad (5)$$

Comparison models

Three simplified models were used for comparison purposes, these being the Newton model, the Henderson and Pabis model, and a two-term Newton model, as expressed below, respectively (Akpinar 2006):

$$\Psi_t = e^{-B_0 t} \quad (6)$$

$$\Psi_t = A_1 e^{-B_1 t} \quad (7)$$

$$\Psi_t = e^{-(B_2 + B_3)t} \quad (8)$$

These first two models do not take into account the distinction of the differences in the mass transfer through the sides and ends of the stalks, as these are lumped together into one term. However, they have been added to determine the necessity and accuracy of using more complex models. The two-term Newton model, however, was used to determine the differences in the moisture migration in the axial and radial directions.

Statistical indicators and analysis

The models were compared primarily on the coefficient of determination (R^2) and the reduced chi-square (χ^2), which is defined as (Akpinar 2006):

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(\psi_{\exp,i} - \psi_{\mathrm{pre},i}\right)^2}{N-n} \quad (9)$$

where $\psi_{\exp,i}$ *and* $\psi_{\mathrm{pre},i}$ are the experimental and predicted moisture ratios, respectively, N is the number of observations and n is the number constants.

The results were analyzed statistically using a general linear model. Mean differences were detected using Duncan's test and determined to be significantly different at $P<0.05$. The trials with the sorghum stalks split longitudinally were not included in the statistical analysis as these trials were of a different geometry that was not representative of the model presented in equations 2-4. The statistical results were obtained using IBM® SPSS® Statistics 19.0.

RESULTS AND DISCUSSION

Drying results

Stalk diameters averaged 11.2 +/-1.9 mm. The equilibrium moisture content is needed to fit the coefficients of the models. Though the drying duration for many of the samples did not allow for equilibrium to be reached, all samples should reach the same equilibrium moisture content given significant duration. This value was approximated by finding the equilibrium moisture content of the stalks that had been split lengthwise, as these samples reached steady-state moisture content during the last portion of the drying tests. This equilibrium moisture content was 0.04 kg/kg.

A typical drying curve for the four treatments is shown in Fig. 1. The sorghum stalks that were split lengthwise demonstrated the least resistance to moisture removal, reaching essentially a steady state value after approximately 20 hours of drying at 50°C and 0.5 m/s air velocity. The axial diffusion and end effects are apparent

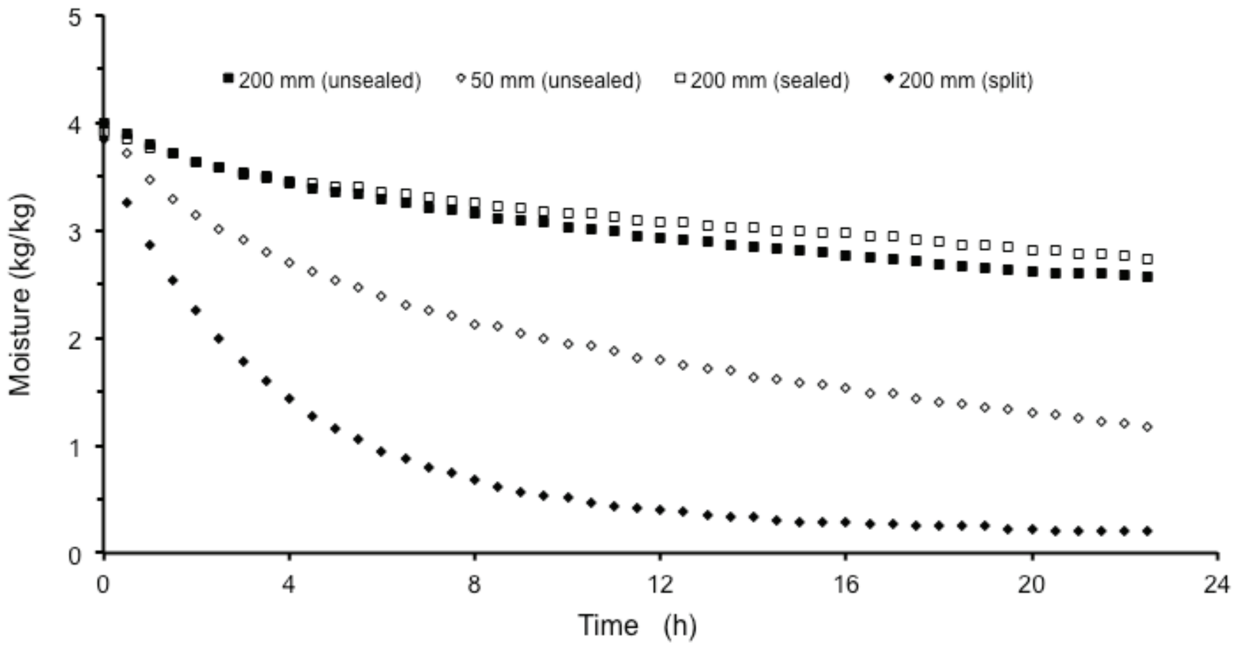

Fig. 1. Typical drying curves of the dry basis moisture content (kg moisture/kg dry solids) versus time (h) for each of the treatments.

when comparing the 50 mm and 200 mm pieces with unsealed ends. After 22 hours of drying, the 50 mm pieces are at roughly 1.2 kg/kg of moisture, whereas the 200 mm pieces are at 2.6 kg/kg. The 200 mm lengths with sealed ends, representing an infinite cylinder, were at 2.8 kg/kg.

The results are interesting in terms of the difficulties that could occur in the field drying of sorghum, as 22 hours of uninterrupted drying at 50°C resulted in minimal moisture removal for longer sorghum pieces. In a typical field-drying situation, the whole intact stalk would be drying as an infinite cylinder at a lower temperature, with a portion of the stalks within a windrow and not subjected to airflow over the stalk surface. Furthermore, minimal drying would occur during the evening and night, and there would be the possibility of surface moisture from dew that would need to be removed the subsequent day.

Comparison of drying models

For every trial performed, each of the four models was fitted to the data. The results from the Newton model are reported in Table 2. As expected, the larger the value of the exponent B_0, the greater the drying rate. The differences in the drying rate between the 50 mm and 200 mm pieces are apparent, along with the effects of sealing the ends when comparing the 200 mm pieces. The Newton model had the best fit when the stalk was split longitudinally. This is not a surprising result, as the flesh of the stalk is highly exposed to the drying environment and there are no competing resistances for moisture removal. The other treatments did not fit the model as well.

One of the drawbacks to models that predict that the drying is based purely on a single exponential function is that it does not take into account that there may be multiple drying effects occurring. The time required to bring the sample to the drying temperature and the time required to remove any surface moisture are secondary effects and tend to modify the drying curve away from being purely exponential. Furthermore, the sorghum stalk contains layers of material, with changes in physical properties from the inside to the outside. These differences can be detected when the Henderson and Pabis model is used. If the curves are purely exponential, then one would expect the exponents in both the Newton model and the Henderson and Pabis model to be identical; with the multiplying factor,

Table 2. Model results: Newton model.

Treatment	Length (mm)	B_0 (1/hr)	χ^2	R^2
None	50	0.0736[a]	0.01321	0.9488
None	200	0.0378[b]	0.01700	0.7755
Waxed Ends	200	0.0227[c]	0.00877	0.8593
Split Longitudinally	200	0.2594	0.00283	0.9956

Mean values with the same letter are not significantly different ($P > 0.05$; Duncan test).

Table 3. Model results: Henderson and Pabis model.

Treatment	Length (mm)	A (-)	B_1 (1/hr)	χ^2	R^2
None	50	0.910^{ab}	0.0655^{a}	0.00383	0.9848
None	200	0.900^{a}	0.0280^{b}	0.00466	0.9411
Waxed Ends	200	0.935^{b}	0.0180^{c}	0.00182	0.9715
Split Longitudinally	200	0.957	0.2475	0.00165	0.9975

Mean values with the same letter are not significantly different (P > 0.05; Duncan test).

A, in the Henderson and Pabis model having a value of unity. The results of the Henderson and Pabis model are presented in Table 3. Overall, the Henderson and Pabis model was better suited to the data than the Newton model, as can be seen from the statistical indicators. In each case, the χ^2 was lower and the R^2 was higher for the Henderson and Pabis model compared to the Newton model. The sorghum stalks split longitudinally, which were well suited to the Newton model, had the multiplying factor, A, the closest to unity of all the models and an exponential value, B, that was very similar to that found with the Newton model. This case is essentially one-dimension diffusion and hence would be expected to behave like a Newton model. Similarly, the stalks with waxed ends are one-dimension diffusion, though with an additional layer of resistance, compared to those split longitudinally. It can be seen that this case was not as close to the Newton model as the multiplying factor was lower. The stalks without waxed ends had further decreases in the multiplying factor, as the drying condition become two dimensional, with greater end effects for the 50 mm pieces. It can be seen from the multiplying factor that the drying curve diverged further away from the Newton model as the end effects became more prominent.

The results from the two-term Newton model are presented in Table 4. The 200 mm stalks with waxed ends were used to determine B_2 by setting B_3 = 0. The value obtained was then used as a constant for the determination of B_3 in the other trials. The mass transfer model is similar to the Newton model, but has two diffusion coefficients to take into account the two-dimensional nature of the drying of the stalks. The value of B_2 is identical to the value of B_0 in the Newton model for the case of the stalks with waxed ends. Similarly, for the other trials, the exponent B_0 is a linear function of B_2 and B_3. Hence the statistical indicators are identical for the Newton model and the two-term Newton model. The advantage of the two-term Newton model in this case is that it quantifies the difference between the mass transfer through the skin and through the ends of the stalk. As can be seen from the data, the B_3 value is significantly larger than the B_2 value, indicating that on an area basis, there is significantly more moisture loss through the ends than through the skin, as expected due to its waxy nature. The value of B_3, was not significantly different between the two lengths, indicating that it is a good estimation of the B_3 value as it was independent of stalk length, as hypothesized in the model.

Results from the separation of variables model are presented in Table 5. Similar to the two-term Newton model, the 200 mm lengths with waxed ends were used to determine the value of D_s with the assumption that D_e was negligible. The effective diffusivity in the radial direction was 4.17 x 10^{-8} m^2/hr. The model was fitted to the data using 100 terms for both ψ_r and ψ_z. The statistical indicators suggest that this model produced an accurate fit for the data. Despite the differences when comparing D_e values for the 50 mm and 200 mm stalks, there was no significant difference in the values, with an average effective diffusivity of 8.81 x 10^{-6} m^2/hr in the axial direction. The model assumes that there is no shrinkage of the stalk and that the initial moisture is uniform throughout the material. Although some shrinkage would be expected, and the material is not homogenous, the results indicate that the use of the separation of variables model is appropriate for the drying of sorghum stalks. The more terms used in the model resulted in an increasing accuracy of the fit. A single term resulted in the least desirable fit, as it fixed the starting dimensionless moisture at 0.561 (refer to Eq. 5). The results indicate that a separation of variable model can be used to successfully determine the effective diffusivity coefficients in two-dimensional drying.

Table 4. Model results: Two-term Newton model.

Treatment	Length (mm)	B_2 (1/hr)	B_3 (1/hr)	χ^2	R^2
None	50	0.0227†	0.0536^{a}	0.01320	0.9488
None	200	0.0227†	0.0151^{b}	0.01700	0.7756
Waxed Ends	200	0.0227	-	0.00877	0.8593

†Set based on B_2 value for 200 mm with waxed ends. Mean values with the same letter are not significantly different (P > 0.05).

Table 5. Model results: Separation of variables.

Treatment	Length (mm)	D_s (m^2/hr)	D_e (m^2/hr)	χ^2	R^2
None	50	$4.17x10^{-8\dagger}$	$6.950x10^{-6\ a}$	0.00786	0.9696
None	200	$4.17x10^{-8\dagger}$	$1.066x10^{-5\ a}$	0.00089	0.9897
Waxed Ends	200	$4.17x10^{-8}$	-	0.00235	0.9688

†Set based on D_s value for 200 mm with waxed ends. Mean values with the same letter are not significantly different (P > 0.05).

CONCLUSION

The drying characteristics of sorghum stalks were determined and the data fit with several models, including two standard exponential models, a two-term Newton model, and a separation of variables model. The standard exponential models provided adequate fit to the data, and tended to have a better fit with the shorter pieces with non-waxed ends. This is attributed to the fact that the resulting drying characteristics are more representative of exponentially decreasing moisture contents. The two-term Newton model was similar to the Newton model, as both are exponential, except that the differences in the mass transfer between the axial and radial directions were deduced. Similarly, the separation of variables model was used to determine both axial and radial diffusion coefficients. The separation of variable model had a better fit to the data than the standard Newton model and the two-term Newton model, whereas the results were on par with the Henderson and Pabis model. The results demonstrated that a separation of variables model can be used to accurately fit two-dimensional drying if an adequate number of terms are included in the model.

NOMENCLATURE

A	Empirical constant in drying models
B	Empirical constant in drying models
D_e	Effective diffusivity on the stalk end (m^2/hr)
D_s	Effective diffusivity on stalk sides (m^2/hr)
n	Number constants (-)
N	Number of observations
r	Radial coordinate (m)
R	Radius (m)
t	Time (hr)
W	Dry basis moisture content (kg/kg)
W_e	Equilibrium dry basis moisture content (kg/kg)
W_i	Initial dry basis moisture content (kg/kg)
W_t	Average dry basis moisture content at time t (kg/kg)
z	Longitudinal coordinate (m)
Z	Half-length of the cylinder (m)
β	Roots of the Bessel function
$\psi_{exp,i}$	Experimental moisture content (-)
$\psi_{pre,i}$	Predicted moisture content (-)
ψ_r	Radial dimensionless moisture (-)
ψ_t	Dimensionless moisture at any time t (-)
ψ_z	Axial dimensionless moisture (-)
χ^2	Chi-square (-)

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