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Drying Characteristics of Forage Sorghum

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ABSTRACT Forage sorghum has been identified as a potential source of biomass for heating by direct combustion. An important aspect of the production system is the drying of the crop prior to storage or processing, such as pelletizing or other forms of densification. It is desirable that the crop can reach a relatively low moisture content with minimal field operations, to reduce energy inputs and minimize production expenses.

In order to properly evaluate the effects of maceration or other similar treatments on the field drying of crops, a baseline of the drying characteristics of the crops 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 20 cm or 5 cm lengths. For some of the 20 cm 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. These trials were compared to a separate run with stalks split lengthwise, which essentially removed the skin resistance. Using the information collected from the dryer, the data were used to determine the diffusion coefficients based on several mathematical models.

Keywords: Drying characteristics, sorghum, biomass crops, diffusion coefficient, modelling.

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 an industry in its infancy, 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 biocrops 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 is of interest is forage sorghum; a crop that has traditionally been used as animal feed. 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. The multiple harvests have the potential to increase the total biomass yield of the crop. However, this requires drying of the crop prior to densification, typically baling, and then possibly pelletizing. Many of the perennial bioenergy crops are harvested either in the late fall or in the spring. This allows for the moisture content of the crops to decrease naturally, as well as permitting some nutrients to leach back into the soil. In general, the moisture content needs to be below 50% to be suitable for combustion (McKendry, 2002b). 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 waxy surface of the stalks and the relatively large thickness of the stalks, may require other field processing, such as maceration, to enhance field drying and to achieve desirable moisture contents for burning.

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. 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 the drying characteristics.

Sampling for Drying Kinetics Samples were collected from the field by cutting the stalks about 20 cm 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).

Sample Preparation The stalks of sorghum were cut into lengths of either 5 cm or 20 cm using a sharp edged knife. Some of the 20 cm stalks were sealed by dipping 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 20 cm stalks were cut in half longitudinally to minimize the effects of the waxy skin. Table 1 details the different treatments. For each treatment, two drying runs were performed. Stalk diameters were measured using calipers.

Table 1. Treatments for the sorghum stalks

Sample	Length (cm)	# Pieces	Treatment
1	20	20	None
2	5	80	None
3	20	20	Waxed Ends
4	20	20	Split Longitudinally

Drying experiments The prepared sorghum stalks were placed in an Armfield UOP8 laboratory-scale dryer 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. Two replicates were performed for each treatment.

Governing differential equation There are several available models to predict the moisture content of an object that is being dried, including models that account for product shrinkage (Rossello et al., 1997). For the sorghum stalks, the geometry can be represented by a finite cylinder. 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).

Mass transfer model For this work, the model assumes that the mass flux can be expressed as a combination of the moisture loss through the sides of the stalk and through the ends. For purposes of simplicity, it is assumed that the moisture content is relatively uniform throughout the stalk and the greatest resistance to mass transfer is close to the surface and the driving force for moisture removal is based on the difference between moisture content and the equilibrium moisture content, W_e. Thus, the simplified mass flux equation is:

$$\frac{\partial m}{\partial t} = -2\pi RL(W - W_e)k_s - 2\pi R^2(W - W_e)k_e \quad (2)$$

where m is the mass of moisture in the sample, k_e and k_s are the mass transfer coefficients on the ends and the sides of a cylinder with radius R and length L. Dividing both sides of the equation by the mass of dry matter will result in an expression for the rate of change of the average moisture content:

$$\frac{\partial W}{\partial t} = -\frac{2\pi RL(W - W_e)k_s}{\rho\pi R^2 L} - \frac{2\pi R^2(W - W_e)k_e}{\rho\pi R^2 L} \tag{3}$$

Integrating and rearranging the above yields:

$$W_t = (W_i - W_e)e^{-\left(\frac{2k_s}{\rho R} + \frac{2k_e}{\rho L}\right)t} + W_e \tag{4}$$

Using the above equation and the data collected during the drying, a non-linear regression was performed with Maple™ 11.02 (Waterloo Maple Inc.) to determine the parameters W_i, W_e, k_s and k_e. However, as k_s and k_e are linearly dependent in the above equation, the value of k_s was determined from the stalks with the waxed ends, assuming $k_e = 0$ and this obtained value was used to determine k_e for the non-waxed stalks.

Separation of variables model The dimensionless moisture at any given time, ψ_t, can be expressed by:

$$\Psi_t = \left(\frac{W_t - W_e}{W_i - W_e}\right) = e^{-\left(\frac{2k_s}{\rho R} + \frac{2k_e}{\rho L}\right)t} \tag{5}$$

As the above relationship considers that the moisture content within the sample is uniform for all times, it is desirable to compare this model to models that account for the non-uniform moisture distribution that occurs during drying. The solution of Equation 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 solution for a finite cylinder. Thus, the moisture ratio at any given time, ψ_t, can be expressed as (Rossello et al., 1997):

$$\Psi_t = \left(\frac{W_t - W_e}{W_i - W_e}\right) = \Psi_r \Psi_z \tag{6}$$

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

$$\Psi_r = \sum_{i=1}^{\infty} \frac{4}{(\beta_i)^2} e^{-\left(\frac{\beta_i^2}{R^2} D_s\right)t} \tag{7}$$

$$\Psi_z = \sum_{i=1}^{\infty} \frac{2}{\left(i - \frac{1}{2}\right)^2 \pi^2} e^{-\left(\frac{\left(i-\frac{1}{2}\right)^2 \pi^2}{Z^2} D_e\right)t} \tag{8}$$

where β_i are the roots of the Bessel function. Taking only the first terms of Equations 7 and 8 yields the following expression for the moisture ratio at any given time:

$$\Psi_t = 0.561 e^{-\left(\frac{5.783}{R^2} D_s + \frac{\pi^2}{Z^2} D_e\right)t} \tag{9}$$

Comparison models Two simplified models were used for comparison purposes, these being the Newton model and the Henderson and Pabis model, as expressed below, respectively (Akpinar, 2006):

$$\Psi_t = e^{-Bt} \tag{10}$$

$$\Psi_t = Ae^{-Bt} \tag{11}$$

These models do not take into account the distinction of the differences in the mass transfer through the sides and ends of the stalks. However, they have been added to determine the necessity and accuracy of using more complex models.

Statistical indicators 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):

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(\psi_{\exp,i} - \psi_{\text{pre},i}\right)^2}{N-n} \tag{12}$$

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

RESULTS AND DISCUSSION

Drying results Stalk diameters averaged 10.0 +/- 1.3 mm. Based on the dry matter in the samples, the dry matter density of sorghum stalks was determined to be 152.6 kg/m^3. These values were used to determine the values for k_s and k_e. The equilibrium moisture content is needed to fit the coefficients of the models. Though the drying duration for many of the samples did allow for equilibrium to be reached, it is hypothesized that regardless of their shape or size, all samples should reach the same equilibrium moisture content. 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 0.14 kg/kg.

A typical drying curve for the four treatments is shown in Figure 1. The sorghum stalks that were split lengthwise demonstrated the least resistance to moisture removal, reaching essentially a steady state value at after approximately 20 hours of drying at 50°C and 0.5 m/s air velocity. The axial diffusion and end effects are apparent when comparing the 5 cm and 20 cm pieces with unsealed ends. After 22 hours of drying, the 5 cm pieces are at roughly 1.2 kg/kg of moisture, whereas the 20 cm pieces are at 2.6 kg/kg. The 20 cm lengths with sealed ends, representing an infinite cylinder, were at 2.8 kg/kg. Although the end effects have a reduced overall effect on the longer pieces, the effects are still apparent.

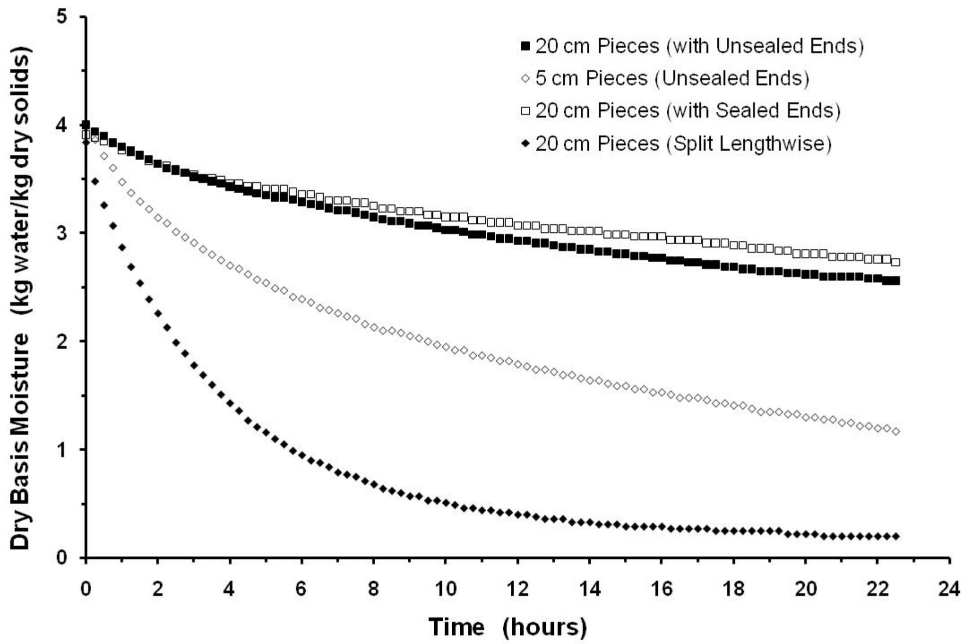

Figure 1. Typical drying curve comparing each of the treatments.

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. 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*, the greater the drying rate. The differences in the drying rate between the 5 cm and 20 cm pieces are apparent, along with the effects of sealing the ends when comparing the 20 cm pieces. The Newton model had the best fit when the stalk was split longitudinal. This is not a surprising result, as the flesh of the stalk is highly exposed to the drying environment and there are not competing resistances for moisture removal. The other treatments did not fit the model as well.

Table 2. Model results: Newton model

Treatment	Length (cm)	*B* (1/hr)	χ^2	R^2
None	5	0.0696	0.03235	0.9033
None	20	0.0269	0.02005	0.8012
Waxed Ends	20	0.0207	0.01271	0.7946
Split Longitudinally	20	0.3009	0.00316	0.9946

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. 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, *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 dimensional diffusion and hence would be expected to behave like a Newton model. Similarly, the stalks with waxed ends are one dimensional diffusion, though an additional layer of resistance. 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 5 cm 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.

Table 3. Model results: Henderson and Pabis model

Treatment	Length (cm)	*A* (-)	*B* (1/hr)	χ^2	R^2
None	5	0.873	0.0568	0.00998	0.9696
None	20	0.917	0.0203	0.00567	0.9437
Waxed Ends	20	0.931	0.0155	0.00338	0.9472
Split Longitudinally	20	0.963	0.2903	0.00196	0.9964

The results from the mass transfer model are presented in Table 4. The 20 cm stalks with waxed ends were used to determine k_s by setting $k_e = 0$. The value obtained was then used as a constant for the determination of k_e 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 stalks. The value of k_s is essentially linearly related to the value of *B* in the Newton model for the case of the stalk with waxed ends. Similarly, for the other trials, the exponent *B* is a linear function of k_s and k_e. Hence the statistical indicators are identical for the Newton model and the mass transfer model. The only advantage to the mass transfer 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 k_e value is significantly larger than the k_s value, indicating that on an area basis, there is significantly more moisture loss through the ends than through the skin, as expected. The value of k_e, however, is much higher for the 5 cm length than for the 20 cm length. This divergence could be attributed to the fact that the model assumes uniform moisture content throughout the stalk at any given time. If the internal resistance to moisture diffusion is much greater than the resistance at the ends of the stalk, then this assumption would no longer be valid.

Table 4. Model results: Mass transfer model

Treatment	Length (cm)	k_s (kg/(m^2·hr))	k_e (kg/(m^2·hr))	χ^2	R^2
None	5	0.00789†	0.1865	0.03235	0.9033
None	20	0.00789†	0.0945	0.02005	0.8012
Waxed Ends	20	0.00789	-	0.01271	0.7946

†Set based on k_s value for 20 cm with waxed ends.

Results from the separation of variables model are presented in Table 5. Similar to the mass transfer model, the 20 cm lengths with waxed ends were used to determine the value of D_s with the assumption that D_e was negligible. The statistical indicators suggest that this model was the most accurate fit for the data. Although the other models tended to have less accurate when the models were applied to the stalks without waxed ends, the separation of variables model still obtained high R^2 values and relatively low χ^2 values. When comparing D_e values for the 5 cm and 20 cm stalks, there is a large difference in the values, much like that noted from the mass transfer model. The ratio of D_e for the 5 cm to the 20 cm stalks was 2.02, compared to a ratio of 1.97 for the k_e values. These ratios were expected to be close to unity. The differences could be attributed to the limited data set used. Further investigation is required to determine the differences observed.

Table 5. Model results: Separation of variables

Treatment	Length (cm)	D_s (m^2/hr)	D_e (m^2/hr)	χ^2	R^2
None	5	2.58×10^{-8}†	7.471×10^{-6}	0.00363	0.9887
None	20	2.58×10^{-8}†	3.693×10^{-6}	0.00183	0.9849
Waxed Ends	20	2.58×10^{-8}	-	0.00127	0.9841

†Set based on D_s value for 20 cm with waxed ends.

CONCLUSION The drying characteristics of sorghum stalks were determined and the data fit with several models, including two standard exponential models, a mass transfer 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 closer to one dimensional. The mass transfer model was similar to the Newton model, as both are exponential, except that the mass transfer coefficients in 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 tended to have the best fit to all the data. The reasons for differences in the axial diffusion coefficients between 5 cm long stalks and 20 cm long stalks needs further investigation by running the model on a larger data set.

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)

k_e Mass transfer coefficient on the end of the cylinder (kg/(m^2·hr))
k_s Mass transfer coefficient on the sides of the cylinder (kg/(m^2·hr))
L Length (m)
m Moisture in sample (kg)
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
ρ Density of dry matter (kg/m^3)
ψ_r Radial dimensionless moisture (-)
ψ_t Dimensionless moisture at any time t (-)
ψ_z Axial dimensionless moisture (-)

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REFERENCES

Akpinar, E.K. 2006. Determination of suitable thin layer drying curve model for some vegetables and fruits. Journal of Food Engineering, Vol. 73(1): 75-84.

Bennett, A.S. and R.P. Anex. 2009. Production, transportation and milling costs of sweet sorghum as a feedstock fro centralized bioethanol production in the upper Midwest. Bioresource Technology, Vol. 100: 1595-1607.

Dandamrongrak, R., G. Young, and R. Mason. 2002. Evaluation of various pre-treatment for the dehydration of banana and selection of suitable drying models. Journal of Food Engineering, Vol. 55(2): 139-146.

Hons, F.M., R.F. Moresco, R.P. Wiedenfeld, and J.T. Cothren. 1986. Applied nitrogen and phosphorus effects on yield and nutrient uptake by high-energy sorghum produced for grain and biomass. Agronomy Journal, Vol. 78: 1069-1078.

McKendry, P. 2002a. Energy production from biomass (Part 1): overview of biomass. Bioresource Technology, Vol. 83: 37-46.

McKendry, P. 2002b. Energy production from biomass (Part 2): conversion technologies. Bioresource Technology, Vol. 83: 47-54.

Rossello, C., S. Simal, N. SanJuan, and A. Mulet. 1997. Nonisotripic mass transfer model for green bean drying. Journal of Agricultural and Food Chemistry, Vol. 45(2): 337-342.

Senadeera, W. B.R. Bhandari, G. Young, and B. Wijesinghe. 2003. Influence of shapes of selected vegetable materials on drying kinetics during fluidized bed drying. Journal of Food Engineering, Vol. 58(3): 277-283.

Türe, S., D. Uzun, and I.E. Türe. 1997. The potential use of sweet sorghum as a non-polluting source of energy. Energy, Vol. 22(1): 17-19.