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# Water relations of drumstick tree seed (*Moringa oleifera*): imbibition, desiccation, and sorption isotherms

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## Summary

Interest in seed propagation of drumstick tree (*Moringa oleifera*) has created a need for information about the water relationships of its seeds. Thus, we studied the imbibition and desiccation kinetics and adsorption/desorption isotherms of drumstick tree seeds. Seeds absorbed water readily when imbibed at 23ºC. After 17 h of exposure to an atmosphere of 100% relative humidity (RH), seed moisture content increased from 10 to 150% on a dry weight basis (dwb). Seeds lost water rapidly in a 1% RH still-air environment, and returned to their original seed moisture content in 24 h, indicating seed covering tissues are highly permeable to water. Adsorption and desorption equilibrium moisture content curves at 25ºC were determined using the dynamic gravimetric method. Drumstick tree seeds equilibrated at relatively low moisture contents over all humidities, remaining below 10% (dwb) at RH levels below 80%. Five equations that are used to model seed moisture content as a function of RH were fit to the data using a non-linear regression method (modified Henderson, modified Chung-Pfost, modified Guggenheim-Anderson-de Boer, modified Halsey, and D'Arcy-Watt). The D'Arcy-Watt model resulted in the best fit for predicting the seed moisture content of drumstick tree seeds. In humid environments, drying seeds before long-term storage may increase the longevity of stored drumstick tree seeds.

## Introduction

Development professionals and nutritionists promote the consumption of drumstick tree leaves (*Moringa oleifera* Lam.), a multi-purpose tree species originating from the sub-Himalayan tract of India, as a food source of vitamin A in tropical and subtropical areas where vitamin A deficiency is prevalent (Coote *et al.*, 1997; Babu, 2000; Seshadri and Nambiar, 2003; Munyanziza and Sarwatt, 2003). Other uses of drumstick tree products include water purification, oil, and supplemental animal feed (Jahn, 1986; Sarwatt *et al.*, 2002; Anwar and Bhanger, 2003). In traditional agroforestry production systems in India, drumstick tree is propagated vegetatively via cuttings (Peter, 1979; Morton, 1991). In areas such as West Africa, however, termite damage and excessive desiccation of cuttings have forced growers to produce drumstick trees from seed (Jahn, 1986; Kokou *et al.*, 2001). Widespread interest in seed propagation of drumstick tree has created a need for scientific information about the fundamental characteristics of its seeds. Because of its ability to grow productively in semi-arid environments, agronomists, nutritionists, and development professionals are increasingly using drumstick tree in rural tropical and subtropical areas where growers often store seeds in structures open to the ambient air. Open-air storage conditions do not protect seeds from large fluctuations in temperature and RH levels, which in turn lead to losses of seed viability. By developing effective seed storage protocols, growers can maintain viable seed populations from season to season.

Seed moisture content is one of the most important factors affecting seed longevity in storage. When exposed to air containing water vapor, seed moisture content equilibrates in relation to the relative humidity (RH) of the air surrounding the seeds. In general, as RH of the storage environment increases, seed moisture content correspondingly increases. This process, in turn, decreases seed longevity. Maintenance of seed viability is particularly challenging in tropical environments where stored seeds are often exposed to hot, humid air (Ellis, 1988).

Suboptimal seed storage practices can lead to poor germination and stand establishment of a crop. Because orthodox oilseeds store best at low seed moisture content (typically 4-6% moisture), lowering the RH of the storage air, which thereby reduces the seed moisture content, is an effective method to prolong seed viability in conjunction with temperature management (Ellis *et al.*, 1996; Hartmann *et al.*, 2002). However, the relationship between seed moisture content and RH of the surrounding air is species- and tissue-specific. This relationship is thought to be influenced by the carbohydrate, lipid, and protein composition of the seed as well as the biochemical structure of the surfaces within the seed (Sun, 2002). One of the first steps in developing recommendations regarding seed storage practices for a species is to describe how seed moisture content changes in relation to varying RH, known as a moisture content isotherm (Brooker *et al.*, 1992). Once this relationship is described for a species, further studies can be performed to determine seed longevity at specific RH/temperature combinations. Describing this relationship for drumstick tree may help explain why such different estimates of seed longevity have been reported in the literature. The reported the lengths of time that drumstick tree seeds can be stored without significant loss in viability vary from three months (Sharma and Raina, 1982) to one year (Vijayakumar *et al.*, 1999; Sivasubramanian and Thiagarajan, 1997) or even several years (Jahn, 1986).

Despite the widespread use of drumstick tree throughout Africa, Asia, India, and the Caribbean, little has been recorded about water uptake and loss kinetics of its seeds. One of the first steps in understanding the permeability of seed tissues to water, germination, and dormancy in a species is determining the volume and rate of water uptake and loss (Baskin and Baskin, 2001). In general, when dry seeds come into contact with free soil water, they take up water through a passive process that can eventually initiate germination under proper environmental conditions. Imbibed seeds can also lose water when soil conditions become dry. The rate at which seeds take up and lose water varies by species, and is predominantly determined by differences in seed tissue permeability (Vertucci, 1989).

The aim of this study was to describe water relations in drumstick tree seed (*M. oleifera*). First, the time courses during which seeds take up and lose water were determined. Second, we described how the RH of the surrounding air affected seed moisture content. Because drumstick tree seeds contain 30-40% oil, we expected to observe low equilibrium moisture contents at any given humidity relative to seeds with lower oil content. Predictions about the rate of water uptake based on the ratio of lipid, protein, and carbohydrate are not likely to be valid since water uptake rates are not primarily controlled by the seed's chemical composition (Vertucci, 1989).

## Materials and methods

*Imbibition*

Five sets of ten *M. oleifera* seeds were weighed and placed in a porous ceramic funnel lined with filter paper moistened with distilled water under laboratory conditions at 23ºC. This container was used to provide enough moisture to allow water uptake by the seeds, but to prevent the seeds from being immersed in water. Each set was weighed every 8-10 min for the first two hours, every 15 min for the next nine hours, then periodically for the next ten hours until seeds stopped gaining water weight. Distilled water was added to the filter paper between weighing events and was allowed to drain before the seeds were returned to each funnel. After 24 h, the seeds were placed in a 103ºC oven for 24 h then weighed. Seed moisture content at each imbibition time was calculated on a dry weight basis (dwb) as

$$\frac{(\text{seed weight} - \text{oven dry weight})}{\text{oven dry weight}} \quad (1)$$

*Desiccation*

As is often the case with studies of tropical tree seeds (e.g., Pammenter *et al*., 1998), supplies of seeds were limited, so desiccation and equilibrium moisture content experiments utilized careful measurements of individual seeds as replicates. Ten drumstick tree seeds were weighed and then imbibed for 24 h by placing them in a Petri dish on blotter paper saturated with distilled water under laboratory conditions at 23ºC. After imbibition was complete, the seeds were weighed and placed in a sealed, still-air container over concentrated sulfuric acid to establish 1% RH in the container atmosphere. Each seed was weighed every 20-30 minutes for the first 4 hours, every 45 minutes for the next 4 hours, then periodically thereafter for the next 22 hours. Dry weights were determined after drying at 103ºC for 24 h and seed moisture contents were calculated as in equation 1.

*Equilibrium Moisture Content*

Equilibrium moisture content was studied using the dynamic gravimetric method. Eleven air-tight containers were constructed out of plastic food storage containers and kept in a controlled environment room at 25ºC (± 1ºC). The bottom half of a Petri dish was placed in the bottom of each container, filled with one of eleven saturated salt solutions with excess salt, and left uncovered. Hardware cloth was used to form a mesh stand to hold the seeds above the saturated salt solution while allowing free air flow inside the container. A small computer fan was attached to the lid of each container to ensure adequate air mixing. Twelve seeds were placed in each container simultaneously; six of the twelve seeds had been placed in a 25% RH chamber for one week prior to being placed in each of the eleven containers, and the six remaining seeds had been imbibed with distilled water for 24 h before being placed in the each container. A total of 132 seeds were used. Each seed was weighed daily for six days, by which time they had achieved equilibrium (see Results). After the seeds were weighed on the sixth day, dry weights were determined as described above. The saturated salt solutions used and the RHs associated with them are listed in table 1. The chamber with distilled water was assumed to provide an environment with about 97% RH.

Table 1. Relative humidities associated with saturated salt solutions used in this study.

| Saturated Salt | Relative Humidity Level (%) |
|---|---|
| $H_2SO_4$ | 1 |
| NaOH | 7.5 |
| Potassium acetate | 25 |
| $MgCl_2$ | 32.5 |
| $K_2CO_3$ | 43 |
| $Mg(NO_3)_2$ | 50.5 |
| $NH_4NO_3$ | 62 |
| NaCl | 75 |
| KCl | 85 |
| $KNO_3$ | 91 |
| Distilled water | ~97 |

(Rockland, 1960; Winston and Bates, 1960; Young, 1967) cited in (Sun, 2002).

*Data Analysis*

Five widely recognized equations that are used to model equilibrium moisture contents (EMC) of seeds and grains (listed in table 2) were fit to the collected data.

Table 2. Equilibrium moisture content-relative humidity (EMC-RH) relationships used to analyze drumstick tree EMC-RH data.

| Formula Name | Equation |
|---|---|
| Modified Henderson | $1 - RH = \exp[-A\ (T + C)M^B]$ |
| Modified Chung–Pfost | $RH = \exp[-A/(T + C)\exp(-B\ M/100)]$ |
| Modified Guggenheim–Anderson–de Boer (GAB) | $M = ABC\ RH/[(1-B\ RH)\ (1-B\ RH + B\ C\ RH)]$ |
| Modified Halsey | $RH = \exp[-\exp(A + B\ T)\ M^{-C}]$ |
| D'Arcy-Watt | $M = \frac{KK'RH}{1 + KRH} + cRH + \frac{kk'RH}{1 - kRH}$ |

(Vertucci and Leopold, 1987; Santalla and Mascheroni, 2003)

In the first four equations in table 2, $M$ is the predicted equilibrium moisture content (decimal), RH is the relative humidity, $T$ is the absolute temperature, and $A$, $B$, and $C$ are model parameters.

These equations were fit to the equilibrium moisture contents of all seeds (12 seeds per humidity level) using the standard non-linear regression method in JMP v. 5.0.1 (SAS Institute, Inc.). The replications measured at 97% relative humidity were excluded from this analysis for two reasons. First, the possible presence of fungi on the seeds could have caused the estimates of seed moisture content to be questionable. Second, forcing the equation to fit the data at 97% humidity often resulted in poor fit at the rest of the humidity levels. Both the standard error of the estimated values ($E_s$) and the mean relative percent deviation (P) were used to evaluate the fit of EMC models. Lower $E_s$ and P values indicate a closer fit with the original data.

The standard error of the estimated value ($E_s$) was calculated as

$$E_s = \sqrt{\frac{\sum (Y - Y')^2}{df}} \qquad (2)$$

The mean relative percent deviation (P) was calculated as

$$P = \frac{100}{N} \sum \frac{(Y - Y')}{Y} \qquad (3)$$

Where *Y* is the measured value, *Y'* is the predicted value, *df* is the degrees of freedom of the regression model, and *N* is the number of data points. Plots of the residual versus the predicted values should be random and centered around zero.

## Results

*Imbibition*

Drumstick tree seeds absorbed water rapidly during the first three hours of imbibition (figure 1). Uptake slowed after the first two hours, but continued until about 17 h, when seed moisture content averaged 150% (dwb).

*Desiccation*

Imbibed seeds lost water rapidly. The rate of water loss was most rapid immediately after the seeds were removed from moist conditions and decreased progressively as time passed (figure 2). Seed moisture content was plotted versus log time, and a linear relationship emerged (see inset in figure 2, $r^2 = 0.974$) indicating the data followed an exponential decay curve as described in equation 4.

Seed moisture content (% dwb) = -76.4(log *t*) + 114.2 (4)

After 24 hours, seeds had dried to their average initial air-dry moisture content depicted in figure 2.

*Equilibrium Moisture Content*

In order to ensure that the seed moisture contents of both the imbibed and air-dry seeds had come into equilibrium with the relative humidity level within each chamber, each seed was weighed daily to gauge water gain or loss. The graphs in figure 3 display the

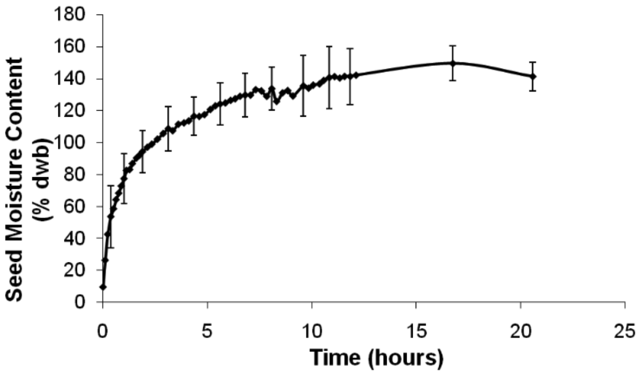


Figure 1. Water uptake of *M. oleifera* seeds over time. Error bars indicate ± 1 SD.

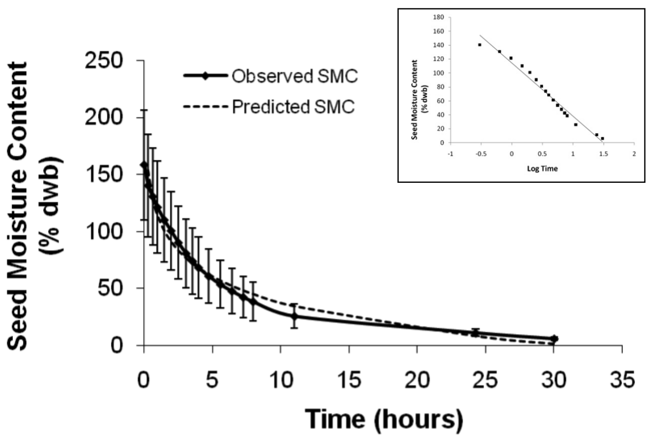


Figure 2. Water loss of *M. oleifera* seeds over time in a 1% RH environment. Error bars indicate ± 1 SD.

least square mean seed moisture content in each chamber over time. Least square mean seed moisture contents were estimated through a repeated measures MANOVA analysis with each seed constituting a replication within a humidity treatment (figure 3). The seed moisture contents equilibrated with the humidity in their respective chambers within the six-day incubation period. Furthermore, both the imbibed and air-dry seed treatments converged to similar seed moisture contents in most containers, although in two containers (62 and 75% RH) the two treatments equilibrated at slightly different seed moisture contents, resulting in the hysteresis observed in figure 4. The equilibration process was somewhat slower for seeds in the highest and lowest humidity levels.

There were two anomalous results on day 4. At 1% RH, there was a slight increase in seed moisture content for the initially imbibed seeds. This appears to be the result of one abnormally large recorded weight for an individual seed, and probably represents a data measurement or recording error. The other unexpected data point is an unusual drop in seed moisture content of the fully imbibed seeds on day 4 at 91% relative humidity. Four seeds in this treatment were recorded to have unusually low weights that day. Why

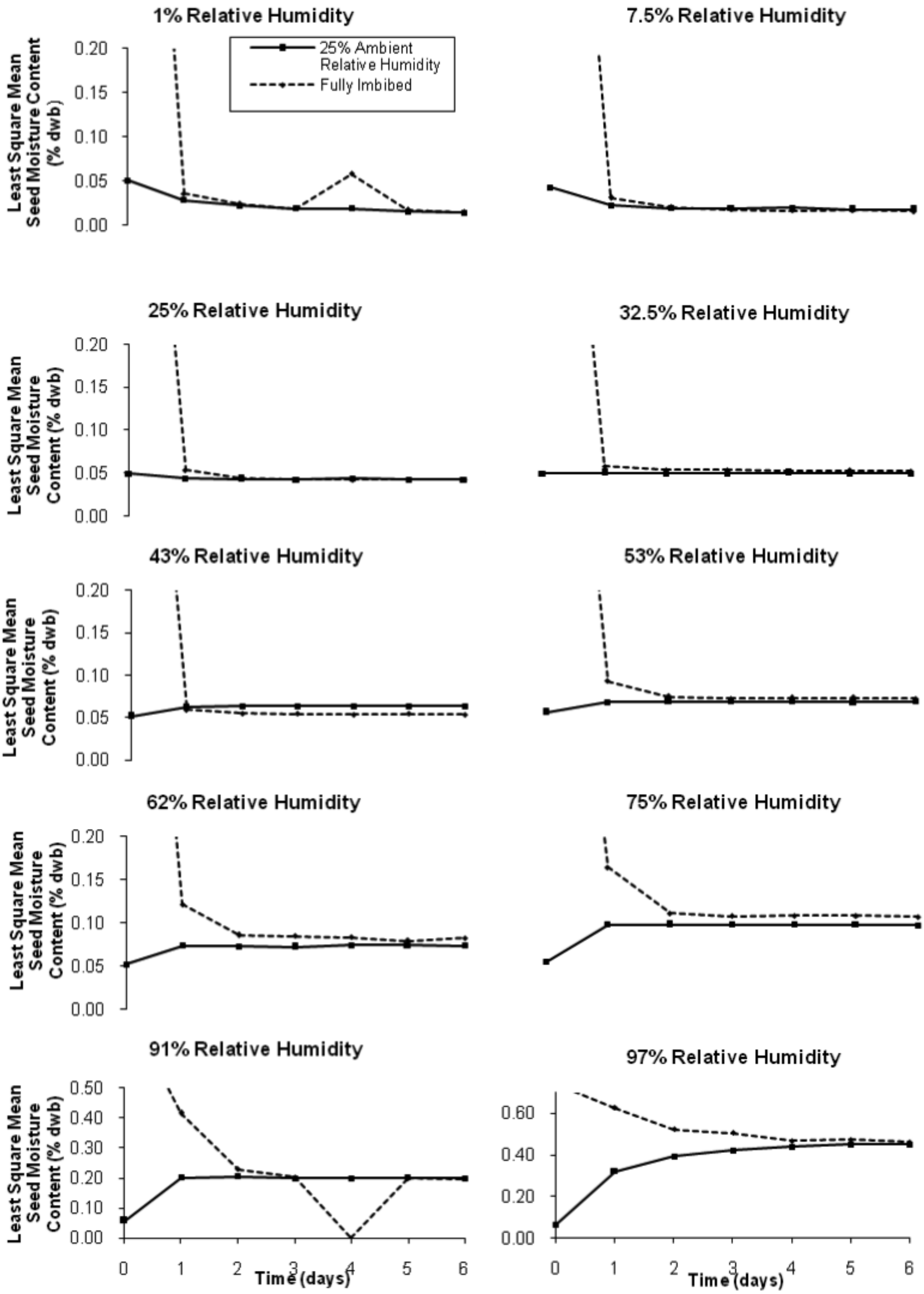


Figure 3. Water loss or gain of *M. oleifera* seeds over time at various ambient relative humidity levels.

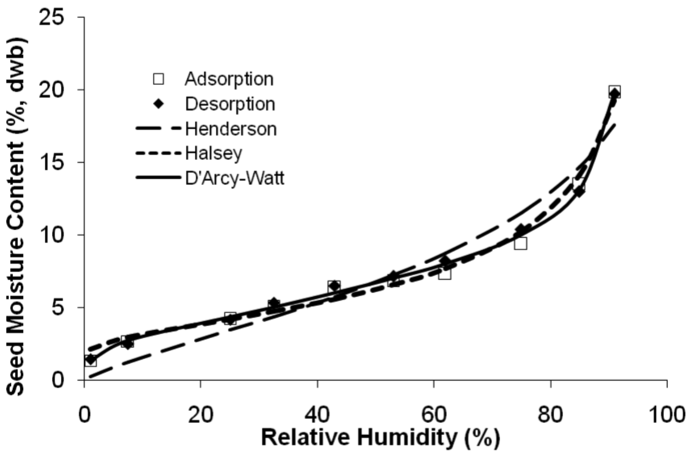


Figure 4. Equilibrium moisture content of drumstick tree seeds predicted by modified Henderson, modified Halsey, and D'Arcy-Watt equations compared to the actual data.

this occurred is not clear, but it could represent an experimental error (e.g., the lid of the container was not closed tightly that day) or a measurement error (e.g., inaccurate taring of the scale). Nonetheless, since the seed moisture contents converged to a similar value in each treatment, we assumed that the seed moisture contents on day six in figure 3 represent equilibrium values at the respective humidity levels.

The seed moisture content isotherm is depicted in figure 4 (open and closed symbols). When exposed to relative humidity levels ranging from 1 to 97%, the average seed moisture content of drumstick tree seeds remained below 10% at RHs less than 80%. At humidity levels greater than 80%, seed moisture content increased rapidly to about 45%. As observed in other equilibrium moisture content studies, slight hysteresis was observed at 62 and 75% RH with the desorption observations displaying slightly higher seed moisture content than the adsorption observations (Sun, 2002).

Once the estimates of drumstick tree seed moisture contents were obtained at 11 RH levels, equations to model the seed moisture content isotherms at any RH were compared (table 2). Each of these equations provides different advantages. The empirically-based modified Henderson and modified Chung-Pfost equations are advantageous because they can be successfully applied to some seeds, grains in particular, without requiring the determination any equation coefficients beforehand (Brooker *et al*., 1992). The modified GAB equation has proven to be the most successful equation to predict moisture content of a wide variety of substances (Brooker *et al*., 1992), while the modified Halsey equation has been successfully applied to seeds high in oil and protein (Santalla and Mascheroni, 2003). The D'Arcy-Watt equation, perhaps the model most widely applied to seeds, has separate terms for the low, middle, and upper sections of the curve, thereby allowing greater accuracy when more than one type of sorption site is present in a material or tissue (Sun, 2002). Of the four equations fit to the data, the D'Arcy-Watt equation gave the best fit since it produced the lowest standard error ($E_s$) and mean relative percent deviation (P) (table 3).

Table 3. Estimated regression coefficients and model fit parameters for the application of five EMC-RH models to drumstick tree seeds.

| Estimated Parameter | Modified Henderson | Modified Chung-Pfost | Modified GAB | Modified Halsey | Estimated Parameter | D'Arcy-Watt |
|---|---|---|---|---|---|---|
| *A* | 4.64 | 41.39 | -108222 | -5.3374 | *K* | 118.4 |
| *B* | -293 | -287.90 | 0.346829 | 0.0002 | *K´* | 0.0237 |
| *C* | 1.30 | 23.11 | -0.0007 | 1.77 | *c* | 0.0754 |
| | | | | | *k* | 1.0436 |
| | | | | | *k´* | 0.0056 |
| $E_s$ (%) | 1.46 | 1.72 | 1.86 | 0.94 | | 0.79 |
| P (%) | 14.04 | 9.48 | 21.53 | 5.95 | | 1.06 |
| Residuals | Patterned | Patterned | Patterned | Patterned | | Random |

When the seed moisture content values predicted by the three equations that produced the lowest values for $E_s$ were compared with the observed values, the better fit of the D'Arcy-Watt equation was evident (figure 4).

The plot of residual values as a function of predicted values for the D'Arcy-Watt equation was random and centered around zero (figure 5). However, similar plots of the four remaining models contained clear patterns, which indicate significant lack of fit between the data and the models. At low RH levels, the models other than the D'Arcy-Watt equation predicted lower seed moisture content than recorded. Likewise, at higher RH levels, the same four models predicted higher seed moisture content than expected. These results further support the conclusion that the D'Arcy-Watt equation provided the best fit for this data set. Therefore, we conclude that the D'Arcy-Watt equation can be used to predict the seed moisture content of drumstick tree seeds using the estimated parameters reported in table 3. Since the measurements from the 97% humidity level were excluded from this analysis, the values predicted by these equations are only valid at 91% RH and below.

## Discussion

The rates of seed imbibition and desiccation are controlled by the water potential gradient between the seed and its environment and the permeability of seed covering tissues to water movement (Vertucci, 1989). Drumstick tree seeds readily take up and lose water to their environment (figures 1, 2), indicating the presence of permeable seed covering tissues. Drumstick tree seeds appeared to complete both of the processes of imbibition and desiccation within 24 h or less under conditions of free water for imbibition and extremely dry, still-air conditions for desiccation. From the time courses presented in this study, it appears that the seed tissues of this species present no major barriers to water uptake or loss. The ability of drumstick tree seeds to readily imbibe water supports the assumption that physical dormancy controlled by the outer seed coat is not present in this species, but does not exclude the possibility that other forms of dormancy may exist. Seed drying rates, which involve the phase change of water in seed tissue from the liquid phase to the vapor phase, is influenced by temperature, the size and shape of seeds, RH of the surrounding air, light conditions, the rate of air flow across the seed surface, and the quantity of seeds being dried (Pammenter *et al.*, 2002). While we did not test all of these parameters, our time course of dehydration of drumstick tree seeds indicates that the seeds can readily exchange water with their gaseous environment (figure 2).

Equilibrium moisture contents of seeds and grains are generally characteristic of a species and are readily comparable across studies (Brooker *et al.*, 1992). Since carbohydrates,

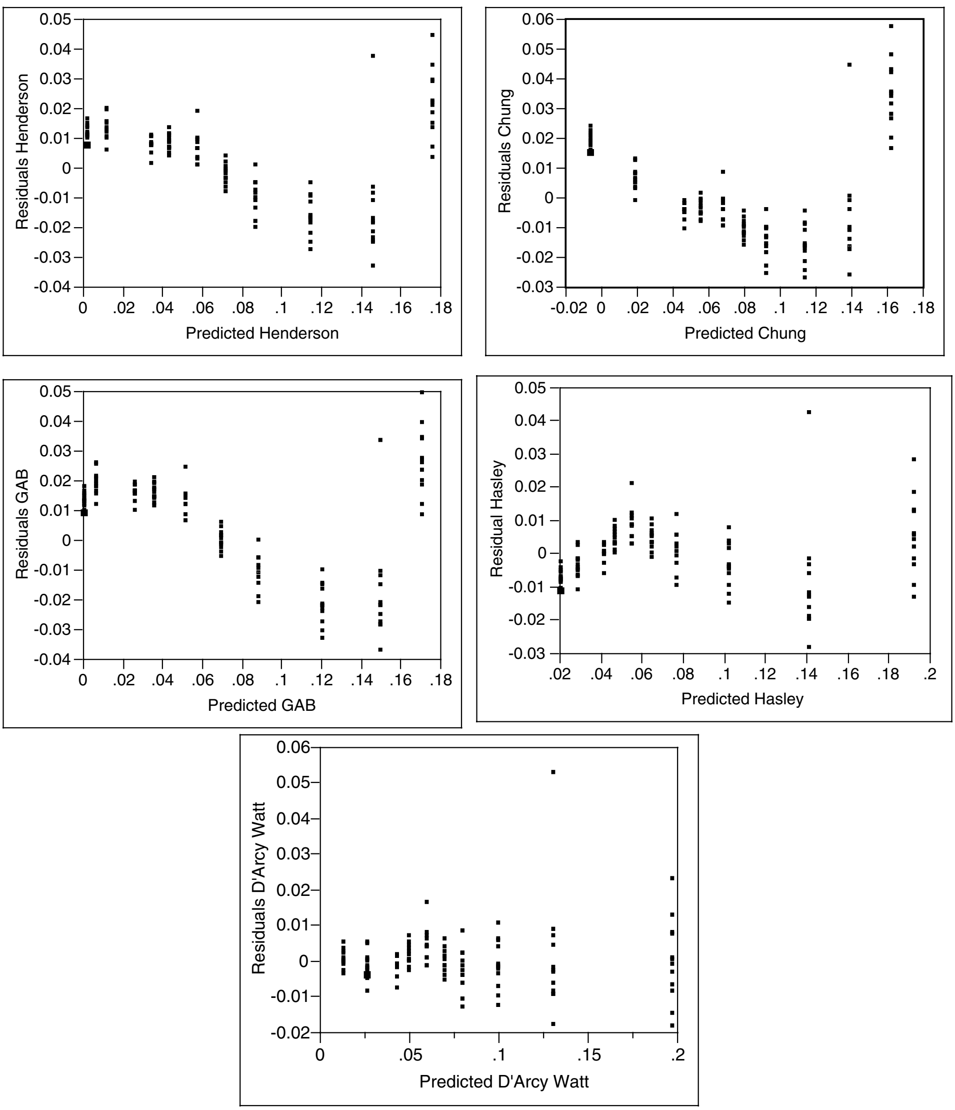


Figure 5. Residual plots of modified Henderson, modified Chung, modified GAB, Hasley, and D’Arcy-Watt equation.

proteins, and lipids all interact differently with water molecules, seeds that contain high amounts of lipids usually equilibrate to lower water contents than starchy seeds at the same RH (Sun, 2002). Like other oilseeds, drumstick tree seeds maintain low seed moisture contents (less than 10%) over a wide range of RH levels. In table 4, the equilibrium moisture content of drumstick tree seeds (wet weight basis (wb)) at 25ºC is compared with eight other grains and seeds at the same temperature. Drumstick tree seeds display a similar pattern to flaxseed, with much lower equilibrium moisture contents than almost all other crops. The only exception is peanut kernel, which shows a lower equilibrium moisture content than drumstick tree over all humidity levels. The observed pattern for drumstick tree seeds is probably due to their high oil content, which is estimated to range between 25 and 50% by weight (Vaughan, 1970; Anwar and Bhanger, 2003). If much of the interior seed volume consists of hydrophobic molecules, there will be fewer hydrophilic surfaces to which water will easily bind.

Table 4. Equilibrium moisture content of grains and seeds at 25ºC (%, wb).

| | Relative Humidity (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Grain or Seed | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| Drumstick Tree (*M. oleifera*) | 3 | 4 | 4.7 | 6 | 6.5 | 7 | 8.2 | 10 | 14 |
| Peanut kernels | -- | 3.0 | 3.9 | 4.7 | 5.6 | 6.5 | 7.5 | 8.8 | 10.6 |
| Flaxseed | 3.8 | 5.0 | 5.5 | 6.1 | 6.7 | 7.7 | 9.2 | 11.2 | 14.9 |
| Soybeans | 3.8 | 5.3 | 6.1 | 6.9 | 7.8 | 9.7 | 12.1 | 15.8 | 21.3 |
| Barley | 4.7 | 6.9 | 8.4 | 9.6 | 10.6 | 11.9 | 13.4 | 15.7 | 19.2 |
| Corn | 5.2 | 7.4 | 8.9 | 10.1 | 11.0 | 12.2 | 13.7 | 15.9 | 19.1 |
| Rice, milled | 4.9 | 7.7 | 9.5 | 10.3 | 11.0 | 12.0 | 13.4 | 15.3 | 18.3 |
| Wheat, hard red winter | 5.0 | 7.2 | 8.2 | 9.9 | 10.9 | 12.1 | 13.8 | 16.0 | 19.4 |
| Dry beans, light red kidney | 5.9 | 7.7 | 9.0 | 9.8 | 11.0 | 12.6 | 15.0 | 18.6 | -- |

(Brooker, Bakkar-Arkema *et al.,* 1992, pp. 69-70)

Like most seed moisture content isotherms, the curve derived from our data for drumstick tree is sigmoidal (figure 4). The sigmoid shape of sorption curves is thought to be caused by the presence of three types of water-binding tissues in seeds including 1) strong, 2) weak, and 3) multilayer molecular sorption sites (Sun, 2002). This concept is mathematically expressed in the D'Arcy-Watt equation. The strong water-binding tissues account for the steep portion of sorption curves at very low humidity levels. There are thought to be hydrophilic surfaces within seeds that bind water very tightly and thus strongly resist dehydration. The interaction of water with the weak water-binding tissues is thought to cause the relatively flat, middle portion of sorption curves. This represents the interaction of water with the less hydrophilic and more hydrophobic surfaces within the seed. When all of the strong and weak hydrations sites of tissues within the seed are saturated with water, the slope of the sorption curve increases sharply. The steep portion of the sorption curve represents the activity of multilayer molecular sorption sites, meaning that water begins to form multiple layers on surfaces within the seed by binding to itself through cohesive forces.

The estimated parameters *K*, *K´*, *c*, *k*, and *k´* in the D'Arcy-Watt equation can be used to infer the water-binding characteristics of seeds (Vertucci and Leopold, 1987). These five parameters contain information about the number of available binding sites for water, as well as the relative affinity of these sites for binding water. The estimates of *K* and *c* for drumstick tree seed reported in table 3 fall within the ranges reported in the literature, 7-200 (dimensionless) for *K* and 0.028 to 0.183 g $H_2O$/g dry weight for *c* (Vertucci and Leopold, 1987). However, the parameters that relate to the number of available water binding sites, *K´* and *k´*, are smaller than the reported ranges of 0.024 to 0.114 g $H_2O$/g dry weight for *K´* and 0.0062 to 0.124 g/g for *k´* (Vertucci and Leopold, 1987). These results suggest that drumstick tree seeds contain fewer sites available to bind water than other seeds, but that the available sites bind water with strength within normal ranges compared with other seeds. This would explain why drumstick tree seeds have a low seed moisture content across all humidity levels—there are simply fewer sites to which water can bind. Seeds with higher lipid contents, like drumstick tree seeds, absorb less water than starchier seeds, presumably because the lipid region is unavailable for water binding (Vertucci and Leopold, 1987). The activity of water, *k*, was estimated to be above one (table 3). While it is not possible for the activity of water to be greater than one, this has been observed in other studies and probably represents slight error in estimating the parameter (Vertucci and Leopold, 1987).

The behavior of water in these three fractions strongly influences viability of seeds during storage. Studies at high temperatures have shown that as the seed dries, the fluidity of the aqueous phase of the seed matrix decreases until the water within the seeds takes on a "glassy" characteristic (Vertucci *et al.*, 1994). The hydration level associated with a glassy water layer is thought to correspond with great reduction in molecular activity within the aqueous phase, but a layer of protective water remains on hydrophylic molecular constituents. This protective water layer maintains intramolecular interactions in proteins and suppresses free radical attack (Vertucci *et al.*, 1994; Berjak, 2006). If seeds are dried beyond this moisture content, irreparable tissue damage can occur.

It is well understood that the longevity of stored seeds increases as seed moisture content decreases (Ellis, 1988; Hartmann *et al.*, 2002). But seed longevity is also strongly influenced by temperature. As a general guideline, for each 1% increase in seed moisture content or alternatively for every 5ºC increase in temperature, seed life is reduced by half (known as Harrington's Rule). Current recommendations state that oil seeds should be stored at lower moisture contents than starchy seeds, namely between 3 and 7% moisture content, with 5% as a reasonable guide (FAO/IPGRI, 1994). It should be noted that drying seeds beyond the critical moisture content either provides no further longevity benefit or alternatively, actually accelerates aging (Wang *et al.*, 2001). This critical value is thought to be associated with the amount of water required to create a protective monolayer of water within the seed on tissues that require binding with water for structural stability (Vertucci *et al.*, 1994).

Such guidelines provide a starting point for developing seed storage recommendations for drumstick tree seeds. However, the conditions to maintain optimum seed viability may be more complex. Vertucci *et al.* (1994) found that the optimum storage moisture content varies with temperature; in particular, lower moisture contents are required as temperature increases. In general, she and her coworkers recommend storing seeds at a moisture content equivalent to the equilibrium moisture content at 20-25% RH at any storage temperature. This corresponds to 4% moisture content (dwb) for drumstick tree seeds. Therefore, 4% should be set as the ideal seed storage moisture content for drumstick tree seeds while acknowledging that 3-7% is probably an acceptable range in practice.

The results from this study can be further expanded into recommendations for growers. Our results suggest that the 3-7% moisture content standard for drumstick tree seeds could be obtained if the environment contains between 20-55% relative humidity under room temperature storage conditions. This would most likely allow a large proportion of the seeds to remain viable. But if RH is greater than 55%, drumstick tree seed longevity could be increased by drying seeds to levels below the equilibrium with the air before storage, and then storing them in an air-tight container in a cool place until use. Since the relative humidity level in tropical areas often exceeds 55%, growers could likely improve seed viability during storage by drying seeds before long-term storage. After seeds are collected, they should be actively dried by a simple hot-air dryer machine and stored in air-tight containers, such as plastic containers, glass jars, or air-tight cans until planting. Due to the financial constraints of many small growers in tropical areas, successful seed storage may be best accomplished by establishing village seed banks.

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