Thin Layer Drying Kinetics of Solar-Dried Amaranthus hybridus and Xanthosoma sagittifolium Leaves

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Abstract

The aim of the study was to model the solar drying characteristics of the leaves of Amaranthus hybridus and Xanthosoma sagittifolium dried in thin layers. Fresh leaves were obtained from Centre for Biodiversity Utilisation and Development (CBUD) farms, trimmed into strips of 0.3 cm x 3 cm and loaded into cabinet solar dryers up to a 5 mm layer. Drying was monitored and moisture loss was determined by loss in weight of samples at hourly interval. Drying data were fitted to five thin layer models, namely; Newton’s, Page’s, Modified Page, Handerson and Pabis and Logarithmic models by Non-linear Regression Analysis, the effective diffusivity was also determined for the two leafy vegetables. All five models showed a good fit between observed and predicted values, with Page’s model resulting in the highest \( r^2 \) and lowest RMSE and \( X^2 \) and hence the best model to describe the solar-drying characteristics of the two vegetables.

Keywords: Drying curves; Effective Moisture Diffusivity; Leafy vegetables; Mathematical modelling; Solar drying

Nomenclature:

- \( a, b, c, k, y \): Constants in models
- \( D_{\text{eff}} \): Effective diffusivity \( m^2/s \)
- \( L \): Half-thickness of slab \( m \)
- \( MR \): Moisture ratio
- \( M \): Moisture content
- \( Mo \): Initial moisture content
- \( N \): Number of observation
- \( r^2 \): Coefficient of determination
- \( t \): Drying time \( \text{min} \)
- \( z \): Number of constants
- \( \exp \): Experimental
- \( \text{pre} \): Predicted

Introduction

Leafy vegetables have gained commercial importance and form an essential part of the Ghanaian diet, providing vitamins and micro-nutrients. As a result of their high moisture and short shelf life, there is the need to process them into stabilized forms with controlled water activity [1] that can store for longer periods [2] so that they will be available all year round [3]. Drying presents one of the most effective methods of food preservation. The process broadly describes these drying characteristics.

The study aimed at observing the drying characteristics of solar-dried Amaranthus spp and Xanthosoma spp leaves in thin layers using five analytical models in order to ascertain the model which best describes these drying characteristics.

Material and Methods

Drying experiments

Fresh fully mature and edible Amaranthus spp (months) and Xanthosoma spp leaves were obtained from the Centre for Biodiversity Utilisation and Development (CBUD) farms at the Amanfrom Prison Camp in Kumasi. The leaves were detached from their stalks and inedible parts removed. The leaves were washed and trimmed into thin strips of dimension (0.3 x 3 cm) spread evenly on drying trays and loaded into a solar cabinet dryer (made of wood with glass windows, schematic in Figure 1 at a density of 1.5 kg/m², in a single layer of 5 mm. Moisture loss during drying was determined by measuring the loss in weight of samples at hourly interval and at the beginning and end of drying and the representative samples are then taken for moisture content determination [7]. The leaves, with initial moisture (wb) content 85.8% and 82.7%, were dried to a final moisture content of 8.5% and 8.9% for Amaranthus spp and Xanthosoma spp leaves respectively. Average drying temperatures over the period of drying in the dryers were 49.8°C (RH 31.3%) and 48.7°C (RH 32.8) (Thermo hygrometer, Hanna HI 91610) for Amaranthus spp and Xanthosoma spp respectively. In

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order to reduce the incidence of moisture reabsorption, drying was discontinued at sundown (30.1°C, RH 47.5% and 30.8°C RH 46.3% for *Amaranthus* spp and *Xanthosoma* spp respectively) and the products were sealed air-tight in polypropylene bags overnight and drying continued the next morning (ambient 24.9°C, RH 69.8%).

**Model fitting of drying data**

Drying data was fitted to the Newton’s, Page’s, Modified Page, Handerson and Pabis and Logarithmic models by Non-linear Regression Analysis (STATGRAPHICS Centurion, 15.1) and coefficient of correlation and goodness of fit of predicted to experimental data determined. The moisture ratio was simplified as \( M/M_o \) because the relative humidity of the inlet air could not be controlled and \( M_i \) is very small as compared to \( M_o \) (Table 1).

The reduced chi square was calculated as:

\[
\chi^2 = \frac{\sum (M_{Re,p,i} - M_{Pr,c})^2}{N - z}
\]  

(1)

**Effective moisture diffusivity**

During drying, a general diffusion transport mechanism in which the rate of moisture movement is described by an effective diffusivity value, \( D_{eff} \) is often assumed, regardless of which mechanism is really involved in moisture movement. In this approach, Fick’s diffusion equation is used to explain the effective diffusivity. Parameters required in this approach are only sample dimensions and the effective diffusion coefficient. This method is very practical and convenient in describing moisture content change during processing. In using Fick’s equation, the leaves used were assumed as slabs and all assumptions for slab-shaped objects were proposed by [8] observed. The effective diffusivity was calculated by a linearised version [9-11].

\[
\ln(MR) = \ln \left( \frac{8}{\pi} \right) - \left( \frac{D_{eff} \times \pi^2 \times t}{4L^2} \right)
\]  

(2)

Where, \( D_{eff} \) is the effective diffusivity (m²/s); \( L \) is half the thickness of the slab (m).

### Results and Discussion

**Drying curves**

The drying curves for the two leafy vegetables show a sample heat-up period where there is little or no drying. This may probably have been due to low temperatures at the beginning of the drying process, and not actually a sample heat-up period that characterises most drying processes.

The drying curves (Figure 2) show an “elbowing” along the curve, which indicates the period between the discontinuation and resumption of drying. The curves show a very short constant rate period as is observed in the drying of most food products [12] and a longer falling rate period, a phenomenon characteristic of food products with water activity less than 1 [13]. This occurrence demonstrates that diffusion is the dominant physical mechanism governing the removal of moisture from the samples. Similar observations were made by [14] for green beans, [15] for red chilli and [16] for okra.

**Mathematical modelling**

The \( r^2 \), RMSE and reduced chi square values for *Amaranthus* and *Xanthosoma* leaves for the chosen models are shown (Table 1). The appropriateness of a model for describing the drying characteristics of samples was based on its \( r^2 \), RMSE and reduced chi-square. The higher the \( r^2 \) values and lower the reduced \( X^2 \) and RMSE values, the better the goodness of fit [17-21] (Table 2).

All five models showed very good fit with \( r^2 \) greater than 0.9 (Table 2). For the two samples studied, the Page model resulted in the highest \( r^2 \) values and corresponding least values for RMSE and reduced chi-square whilst the Newton and Modified Page’s models gave the lowest \( r^2 \) and highest RMSE and reduced chi-square. The high \( r^2 \) for the Page model is an indication that it best describes the thin layer solar drying characteristics of the two leafy vegetables and fitted curve for the model is shown in Figure 3. Similar findings were detailed by [22] for [23].

![Figure 1: Schematics of Solar Cabinet Dryer.](image)

### Table 1: Mathematical models as given by various authors.

<table>
<thead>
<tr>
<th>Model</th>
<th>Name</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR = exp (-kt)</td>
<td>Newton</td>
<td>Liu and Bakker-Arrema (1997)</td>
</tr>
<tr>
<td>MR = exp (-kt)</td>
<td>Page’s</td>
<td>Doymaz (2005)</td>
</tr>
<tr>
<td>MR = exp (-kt)</td>
<td>Modified Page’s</td>
<td>Waewsak et al. (2006)</td>
</tr>
<tr>
<td>MR = a exp (-kt)</td>
<td>Henderson and Pabis</td>
<td>Waewsak et al. (2006)</td>
</tr>
<tr>
<td>MR = a exp (-kt) + c</td>
<td>Logarithmic</td>
<td>Yaldiz et al. (2001)</td>
</tr>
</tbody>
</table>

### Table 2: Models and their respective \( r^2 \), RMSE and \( X^2 \) for *Amaranthus* spp and *Xanthosoma* spp. leaves.

<table>
<thead>
<tr>
<th>Leafy vegetable</th>
<th>Mathematical model</th>
<th>( r^2 )</th>
<th>RMSE</th>
<th>( X^2 )</th>
<th>RMSE</th>
<th>( X^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Amaranthus</em></td>
<td>MR = exp (-kt)</td>
<td>0.9236</td>
<td>0.1017</td>
<td>0.0100</td>
<td>0.9343</td>
<td>0.0914</td>
</tr>
<tr>
<td><em>Amaranthus</em></td>
<td>MR = exp (-kt)</td>
<td>0.9917</td>
<td>0.0349</td>
<td>0.0012</td>
<td>0.9905</td>
<td>0.0363</td>
</tr>
<tr>
<td><em>Amaranthus</em></td>
<td>MR = exp (-kt)</td>
<td>0.9236</td>
<td>0.1058</td>
<td>0.0100</td>
<td>0.9343</td>
<td>0.0951</td>
</tr>
<tr>
<td><em>Amaranthus</em></td>
<td>MR = a exp (-kt)</td>
<td>0.9483</td>
<td>0.0870</td>
<td>0.0070</td>
<td>0.9573</td>
<td>0.0767</td>
</tr>
<tr>
<td><em>Amaranthus</em></td>
<td>MR = a exp (-kt) + c</td>
<td>0.9699</td>
<td>0.0893</td>
<td>0.0086</td>
<td>0.9791</td>
<td>0.0561</td>
</tr>
<tr>
<td><em>Xanthosoma</em></td>
<td>MR = exp (-kt)</td>
<td>0.9483</td>
<td>0.0870</td>
<td>0.0070</td>
<td>0.9573</td>
<td>0.0767</td>
</tr>
<tr>
<td><em>Xanthosoma</em></td>
<td>MR = exp (-kt)</td>
<td>0.9343</td>
<td>0.0951</td>
<td>0.0091</td>
<td>0.9343</td>
<td>0.0951</td>
</tr>
<tr>
<td><em>Xanthosoma</em></td>
<td>MR = a exp (-kt)</td>
<td>0.9483</td>
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<td>0.9791</td>
<td>0.0561</td>
</tr>
</tbody>
</table>

Figure 2: Drying curves for *Amaranthus* spp and *Xanthosoma* spp.

**Effective moisture diffusivity calculation**

A plot of ln(MR) against time t, gives a line with slope:

\[
\text{Slope } = -\frac{\pi D_{eff}}{4L^2}
\]

The slope, effective diffusivity \(D_{eff}\), the corresponding values of coefficients of determination \(r^2\) and the reduced chi square \(X^2\) for the two indigenous leafy vegetables are presented (Table 3) (Figures 4 and 5). The effective diffusivity, \(D_{eff}\), for the two leafy vegetables are comparable to 6.4 x 10^{-9} m²s⁻¹ as obtained by [26] for drying carrots at 64°C and 1.2 x10⁻⁹ m²s⁻¹ – 5.9 x10⁻⁹ m²s⁻¹, by [27] for carrots dried at 30 and 70°C. Again it was within the range of 3.8 x10⁻¹⁰ m²s⁻¹ –1.2 x 10⁻¹⁰ m²s⁻¹ for drying green pepper at 60-80°C [28] and 6.03x10⁻⁹ m²s⁻¹–3.15 x10⁻⁸ m²s⁻¹ for vegetable wastes in a temperature range of 50–150°C [27]. At higher drying temperatures, the effective diffusivity is expected to be higher, especially with an increase in the drying air velocity [28,21,29].

![Figure 3: Fitted drying curve for leafy vegetables using Page's model.](image)

**Table 3:** Effective diffusivity, slope, reduced \(X^2\) and co-efficient of determination for the leafy vegetables.

<table>
<thead>
<tr>
<th>Leafy Vegetable</th>
<th>Slope (D_{eff}) x10⁻⁹ m²s⁻¹</th>
<th>(X^2)</th>
<th>(r^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Amaranthus spp</em></td>
<td>0.1766</td>
<td>1.95</td>
<td>0.0200</td>
</tr>
<tr>
<td><em>Xanthosoma spp</em></td>
<td>0.1682</td>
<td>2.09</td>
<td>0.0086</td>
</tr>
</tbody>
</table>

![Figure 5: Linear relationship between ln MR and drying time for *Xanthosoma spp*.](image)

**Figure 5:** Linear relationship between ln MR and drying time for *Xanthosoma spp*.

**Conclusion**

The results show that the change in moisture ratio over time for solar drying the two leafy vegetables can be best described by the Page’s model. Under similar drying conditions, the model is appropriate for simulating the outcome of drying these vegetables during process control. Effective Moisture Diffusivity ranged between 1.9x10⁻⁹ m²s⁻¹ and 2.1 x 10⁻⁹ m²s⁻¹ for the two leafy vegetables.

**References**