MODELING DRYING CHARACTERISTICS OF MORINGA (MORINGA OLEIFERA) LEAVES UNDER A MECHANICAL CONVECTIVE CABINET DRYER

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Abstract
Moringa oleifera leaves is known for its nutritive and medicinal relevance especially because almost every part of the plant can be used as medicine, food or other beneficial applications. In this study, drying characteristics of Moringa oleifera leaves were investigated using a Mechanical Convective Cabinet dryer at temperature of 45, 55, 65 and 75°C and at constant air velocity of 0.9 m/s. Thirteen (13) Mathematical models were fitted to the experimental data and the performance of these models was evaluated by comparing the coefficient of determination \((R^2)\), Root Mean Square Error (RSME) and reduced chi-square \((\chi^2)\) between the observed and predicted moisture ratio for all conditions of drying. Results indicated that drying took place in the falling rate period as there was only a very short or no constant rate period in the drying curves. Also, there was a reduction in drying time and an increase in drying rate as the drying air temperature increased. Mathematical modeling of the drying characteristics showed that diffusion model gave the best for Moringa oleifera samples dried at 45 and 55°C while the Simplified Fick’s (SFFD) diffusion was the best model for 65 and 75°C. The dried vegetables can be rehydrated and used in ready to eat foods.

Keywords: drying, Mathematical models, falling rate period, drying temperature, air velocity

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1. INTRODUCTION

Moringa oleifera is the most widely cultivated species of the genus Moringa. It is the only genus in the family Moringaceae. Almost every part of the Moringa tree can be used for food or medicine. Due to its vast application, people also often called ‘Miracle Tree’. Some nutritional and medicinal properties of Moringa oleifera leaves have been reported (Fahey, 2005). Drying is a very important way of preserving foods of all variety and it has been utilized for this purpose for several years now. Drying involves the removal of moisture from a material by the application of heat (Ching et al., 2012). This is done so that the product can attain a safe moisture content which is necessary for longer shelf life in storage. It is energy intensive. In other words, drying can also be considered as a combined simultaneous heat and mass transfer operation which involves a continuous supply of energy. The major objectives of drying are to extended shelf life as well as enhance quality, ease handling, for further processing and for sanity of operations. It is one of the oldest methods of preserving food which has been practiced by mankind (Mujumdar, 2007). The drying process of agricultural products can be undertaken in closed equipment such as a solar or industrial dryer to improve the quality of the final product (Ertekin and Yaldiz, 2004). In Engineering, it is important to develop a good understanding of the controlling parameters of this complex process. Hence, mathematical models of the drying processes are used for designing new drying systems or improving existing ones as well as control the drying process. Many mathematical models have used to describe the drying process of the thin-layer drying models of several agricultural materials. Some of the thin-layer drying models, available in literature for explaining drying characteristics of agricultural products, have been highlighted here. These models can be classified as theoretical, semi-theoretical...
(Lewis, Page, Henderson and Pabis, Modified Page, Logarithmic, Two-term, Two-term exponential, Approximation of diffusion), and empirical (Wang and Singh model) (McMinn, 2006). Several researchers have undertaken many studies on mathematical modeling and kinetics of vegetable drying process. For instance, eggplant (Akpinar and Bicer, 2004; Ertekin and Yaldiz, 2004), red chilli (Kaleemullah and Kailappan, 2005), okra (Doymaz, 2005a; Gogus and Maskan, 1999), tomato (Sacilik et al., 2006) and green pea (Simal et al., 1996). However, there is limited information and research on drying of Moringa oleifera leaves in literature.

Various methods of drying fruits and vegetables exist such as the direct sun drying, solar drying, convective or mechanical cabinet drying, freeze drying, oven drying, shadow drying, green-house drying etc. The present study was undertaken with the following objectives:

i. conduct thin layer drying experiment on Moringa oleifera using the mechanical cabinet dryer for four (4) temperatures: 45, 55, 65 and 75°C at constant air velocity of 0.9m/s

ii. evaluate the effect of drying temperatures on the drying characteristics of Moringa oleifera leaves; 

iii. fit the experimental data to thirteen (13) mathematical models in order to determine an appropriate drying model for the Moringa oleifera leaves using relevant statistical methods

2. MATERIAL AND METHODS

The Moringa oleifera leaves used for this experiment was obtained from a commercial at farm Akure, Nigeria and used immediately for the drying experiments. After collecting the Moringa oleifera leaves samples, they were sorted and properly rinsed with water to removed dust and other foreign materials that might be present. The mechanical cabinet dryer were operated at temperatures 45, 55, 65 and 75°C and at air velocity 1.9 m/s. The drying system was first run for about 30 minutes to obtain a stable condition before placing samples in the chamber. The initial moisture content of the samples were determined using the oven method as used by several authors (Owoso and Ogunmoyela, 2001). In this method the material is placed in the oven and set at 102°C to dry for about 24 hours after which the final weight is taken. The initial weights of the Moringa oleifera leaves were about 100±5g and the drying operation started with an initial moisture content of about 75.46% (wet basis) and continued until no further changes in their mass were observed i.e. to the final moisture content of about < 10% (w.b) which was taken as the equilibrium moisture content. This method has earlier been used by McMinn (2006), Setwase et al., (2013) and Karim et al., (2013). Drying tests were conducted in triplicates at each air temperature.

Analysis of drying data

The experimental drying data obtained were fitted to the thirteen (13) thin layer drying models shown in Table 1. The moisture ratio was obtained from equation (1)

\[ MR = \frac{M_t - M_e}{M_0 - M_e} \]  

Where \( M \), \( M_0 \), and \( M_e \) are present, initial and equilibrium moisture contents.

This has been used and simplified by many researchers (Togrul and Pehlivan, 2004; Akpinar, 2006) to the Equation 2 below

\[ MR = \frac{M_t}{M_0} \]  

Where MR= Moisture ratio, \( M_t \) = Moisture content at any time, t, \( M_0 \) = Initial Moisture content, \( M_e \) = Equilibrium moisture content

The drying rate (DR) can be expressed below as reported by Ceylan et al.,( 2007), Doymaz, (2007), and O”zbek and Dadali (2007).

\[ DR = \frac{M_t+M_0-M_t}{t} \]  

where \( M_t+dt \) and \( M_t \) are moisture content at \( t+dt \) (kg water/kg dry matter) and moisture content at time t respectively and t is drying time (min).
Table 1: Thin-layer drying models most frequently used by various authors.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Model Name</th>
<th>Model</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Newton</td>
<td>$MR = \exp^{{tk}}$</td>
<td>Ayensu, (1997); Togrul and Pehlivan, (2004); Upadhyay et al., 2008</td>
</tr>
<tr>
<td>4.</td>
<td>Modified Page II</td>
<td>$MR = \exp(-k(t/L^2))$</td>
<td>Midilli et al., (2002); Wang et al.(2007)</td>
</tr>
<tr>
<td>5</td>
<td>Henderson and Pabis</td>
<td>$MR = a.\exp(-kt)$</td>
<td>Kashaninejad and Tabil (2004); Saeed et al. (2006); Ozdemir and Devres, (1999)</td>
</tr>
<tr>
<td>6</td>
<td>Modified Hend. and Pabis</td>
<td>$MR = a.\exp(-kt)+b.\exp(-gt)+c.\exp(-ht)$</td>
<td>Karathanos, (1999); Kaya et al., (2007b); Yaldiz et al., (2001)</td>
</tr>
<tr>
<td>7</td>
<td>Simplified Fick’s (SFFD) diffusion</td>
<td>$MR = a.\exp(-kt)+c$</td>
<td>Babalis et al., (2006); Ceylan et al., 2007; Lahsasni et al., (2004b)</td>
</tr>
<tr>
<td>8</td>
<td>Logarithmic</td>
<td>$MR = a.\exp^{(0.3L/2)}$</td>
<td>Togrul and Pehlivan, (2002; 2003); Wang et al., (2007)</td>
</tr>
<tr>
<td>9</td>
<td>Two-term</td>
<td>$MR = a.\exp^{(kx)}+b.\exp^{(kx)}$</td>
<td>Lahsasni et al., (2004b); Rahman et al., (1998); Wang et al., (2007)</td>
</tr>
<tr>
<td>10</td>
<td>Two-term Exponential</td>
<td>$MR = a.\exp^{(kx)}+(1-a)\exp^{(kx)}$</td>
<td>Midilli and Kucuk, (2003); Sacilik et al., (2006); Tarigan et al., (2007)</td>
</tr>
<tr>
<td>11</td>
<td>Verma et al</td>
<td>$MR = a.\exp^{(kx)}+(1-a)\exp^{(Ct)}$</td>
<td>Doymaz, (2005b); Karathanos, (1999); Yaldiz and Ertekin, (2001)</td>
</tr>
<tr>
<td>12</td>
<td>Diffusion approach</td>
<td>$MR = a.\exp^{(kx)}+(1-a)\exp^{(kx)}$</td>
<td>Wang et al., (2007); Yaldiz and Ertekin, (2001); Togrul and Pehlivan, (2002)</td>
</tr>
<tr>
<td>13</td>
<td>Wang and Singh</td>
<td>$MR = 1 + at + bt^2$</td>
<td>Wang and Singh, 1978</td>
</tr>
<tr>
<td>14</td>
<td>Thomson</td>
<td>$t = a.\ln(MR) + b[\ln(MR)]^2$</td>
<td>Paulsen and Thomson (1973); Thomson et al., (1968)</td>
</tr>
<tr>
<td>15</td>
<td>Midilli and Kucuk</td>
<td>$MR = a.\exp^{(kx)} + bt$</td>
<td>(Midilli and Kucuk, 2003)</td>
</tr>
<tr>
<td>16</td>
<td>Hii et al.</td>
<td>$MR = a.\exp^{(-kx)} + c.\exp^{(-g^2)}$</td>
<td>Hii et al., 2009</td>
</tr>
</tbody>
</table>

Moisture ratio (MR) = dependent variable, Drying constant (k) = independent variable

Regression analysis was performed using Microsoft Excel Solva version 2007. The coefficient of determination ($R^2$) was the primary criterion used for selecting the best model to describe the drying curves. In addition to $R^2$, the deviations between experimental and predicted values for the models and root mean square error analysis (RMSE) were used to determine the goodness of the fit. The higher the values of $R^2$ and the lower the values of $\chi^2$ and RMSE, the better the goodness of the fit (Midilli and Kucuk, 2003). They were calculated as

$$R^2 = \frac{\sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N} (MR_{exp,i} - MR_{exp,i})^2} \quad (4)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{exp,i} - MR_{cal,i})^2}{N-n} \quad (6)$$

where $R^2$ is called the coefficient of determination, $MR_{exp,i}$ stands for the experimental moisture ratio found in any measurement, $MR_{pre,i}$ is the predicted moisture ratio for this measurement and $N$ is the total number of observations (Demir et al., 2007; Doymaz, 2005b; Wang et al., 2007). Modeling the drying behaviour of different agricultural products often requires the statistical methods of regression models and correlation analysis. Linear and non-linear regression models are important tools to find relationship between different variables, especially for which no established empirical relationship exists.
3. RESULTS AND DISCUSSION

Drying curves

Figures 1 and 2 show the variation of moisture ratios with the drying time and the drying rates versus drying time respectively for *Moringa oleifera* leaves. It is obvious that increasing the drying temperature resulted in an increase in the drying rate, therefore decreasing the drying time. The time required to decrease the moisture content to the given level was dependent on the drying condition, being highest at 45°C (5hrs) and lowest at 75°C (4hrs). It is observed that there was only a short constant rate drying period in the drying of *Moringa oleifera* leaves. Though drying rate was initially low at the start of drying, it suddenly increased sharply and then consistently reduced till the end of the drying period. Majority of the drying took place in the falling rate period. This indicates that diffusion is the main physical mechanism governing moisture migration in the samples. Similar results were obtained by Doymaz (2013) for broccoli, Wankhade *et al.*, (2013) for okra, Lee and Kim (2009) for radish, Kaleemullah and Kailappan (2006) for red chillies, and Togrul and Pehlivan (2003) for apricots. The effect of temperature used for the drying process was most remarkable with moisture content reducing rapidly with increased temperature.

![Figure 1: Variation of moisture content with drying time for Mechanically dried *Moringa oleifera* Leaves](image1)

![Figure 2: Variation of drying rate with drying time for Mechanically dried *Moringa oleifera* Leaves](image2)
This agrees with reports from several researchers who have also reported a significant increase in the drying rates when higher temperatures were used for drying various agricultural products such as chili (Zhao et al., 2013), pepino fruit (Uribe et al., 2011), canola (Gazor and Mohsenimanesh, 2010), okra (Doymaz, 2005a), eggplant (Ertekin and Yaldiz, 2004), and red pepper (Doymaz and Pala, 2002).

**Fitting of the drying curves**

Table 2, presents the results of non-linear regression analysis of the thirteen models. The entire model gave consistently high coefficient of determination ($R^2$) values in the range of 0.803 to 0.994. Table 2 shows the summary of statistical results obtained from mathematical models. The best model describing the thin-layer drying characteristics of *Moringa oleifera* using the mechanical dryer was chosen as the one with the highest $R^2$ values and the lowest $\chi^2$ and RMSE values. Four different temperatures were considered which are 45, 55, 65 and 75°C. The statistical parameter estimations showed that $R^2$, $\chi^2$ and RMSE values ranged from 0.817 to 0.994, 0.0001 to 0.002448, and 0.009761 to 0.046934 respectively for sample dried at 45°C. Also $R^2$, $\chi^2$ and RMSE values ranged from 0.9600 to 0.985, 0.000922 to 0.002904, and 0.0254 to 0.0417 respectively for samples dried at 55°C.

![Graph](image1.png)

**Figure 3:** Plot of Experimented MR against Predicted MR using the Diffusion model for *Moringa oleifera* for the Mechanical Cabinet dryer of the leaves at 45°C

![Graph](image2.png)

**Figure 4:** Plot of Experimented MR against Predicted MR using the Diffusion model for *Moringa oleifera* for the Mechanical Cabinet dryer of the leaves at 55°C
Figure 5: Plot of Experimented MR against Predicted MR using the Simplified Fick’s (SFFD) diffusion model for *Moringa oleifera* for the Mechanical Cabinet dryer of the leaves at 65°C

Figure 6: Comparision of Experimented MR against Predicted MR using the Simplified Fick’s (SFFD) diffusion model for *Moringa oleifera* for the Mechanical drying of the leaves at 75°C

For samples dried at 65°C, $R^2$, $\chi^2$ and RMSE values were ranged from 0.9260 to 0.9910, 0.000981 to 0.008842, and 0.9260 to 0.991000 respectively and for 75°C dried samples, $R^2$, $\chi^2$ and RMSE values were ranged from 0.803 to 0.936, 0.007018 to 0.02255, and 0.06826 to 0.13431 respectively. Of all the models tested, the Hii *et al.*, Diffusion approach, Diffusion approach, Simplified Fick’s (SFFD) diffusion model gave the highest value of $R^2$ and the lowest values of $\chi^2$ and RMSE for 45, 55, 65 and 75°C respectively. Figure 3, 4, 5 and 6 compares experimental data with those predicted with the respective models for *Moringa oleifera* leaves samples for mechanical drying at 45, 55, 65 and 75°C. The prediction using the model showed MR values banded along the straight line with a very high value of $R^2$ (0.994, 0.985, 0.9910 and 0.936 for 45, 55, 65 and 75°C), which showed the suitability of these models in describing mechanical drying characteristics of *Moringa oleifera*. Tables 2 showed that drying rate constants increase with increase in drying air temperature. An increase in rate constant with increasing drying air temperature has been reported by Kaleemullah and Kailappan, (2006) for the drying of red chillies and Olurin *et al.*, (2012) for the drying of Blanched field pumpkin.
Table 2: Drying constants and coefficients of the non-linear regression model for Moringa oleifera leaves

<table>
<thead>
<tr>
<th>MODEL</th>
<th>DRYING AIR TEMP</th>
<th>MODEL CONSTANTS</th>
<th>R²</th>
<th>χ²</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page</td>
<td>45, 55, 65, 70</td>
<td>k=-0.027695033, n=1.920405329</td>
<td>0.9860</td>
<td>0.0003</td>
<td>0.0157</td>
</tr>
<tr>
<td>Simplified Fick's (SFFD) diffusion</td>
<td>45, 55, 65, 70</td>
<td>a=20.98391905, k=-0.004291747, c=-19.93668123</td>
<td>0.9430</td>
<td>0.0010</td>
<td>0.0306</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>45, 55, 65, 70</td>
<td>a=1.0916321, k=0.206395945, c=-0.056499528</td>
<td>0.9790</td>
<td>0.0013</td>
<td>0.0305</td>
</tr>
<tr>
<td>Henderson</td>
<td>45, 55, 65, 70</td>
<td>a=1.085766549, k=0.344036694, c=-0.019151405</td>
<td>0.9750</td>
<td>0.0026</td>
<td>0.0428</td>
</tr>
<tr>
<td>Two-term</td>
<td>45, 55, 65, 70</td>
<td>a=1.022330856, k=0.042469505, c=-0.011270812, g=-0.695614876</td>
<td>0.9940</td>
<td>0.0001</td>
<td>0.0098</td>
</tr>
<tr>
<td>Wang and Singh</td>
<td>45, 55, 65, 70</td>
<td>a=-0.074620416, k=0.00012635, b=-0.007284146, g=-0.069183629</td>
<td>0.8910</td>
<td>0.0017</td>
<td>0.0395</td>
</tr>
<tr>
<td>Midilli and Kucuk</td>
<td>45, 55, 65, 70</td>
<td>a=1.000129587, k=-0.012492689, g=0.020656897, n=1.122828</td>
<td>0.9650</td>
<td>0.0064</td>
<td>0.0240</td>
</tr>
<tr>
<td>Henderson and Pabis</td>
<td>45, 55, 65, 70</td>
<td>a=1.05390941, k=0.10243577, b=0.00012635, g=0.069183629</td>
<td>0.9650</td>
<td>0.0064</td>
<td>0.0240</td>
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<td>Verma et al</td>
<td>45, 55, 65, 70</td>
<td>a=1.05390941, k=0.10243577, b=0.00012635, g=0.069183629</td>
<td>0.9650</td>
<td>0.0064</td>
<td>0.0240</td>
</tr>
<tr>
<td>Diffusion approach</td>
<td>45, 55, 65, 70</td>
<td>a=1.05390941, k=0.10243577, b=0.00012635, g=0.069183629</td>
<td>0.9650</td>
<td>0.0064</td>
<td>0.0240</td>
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<tr>
<td>Hii et al</td>
<td>45, 55, 65, 70</td>
<td>a=1.05390941, k=0.10243577, b=0.00012635, g=0.069183629</td>
<td>0.9650</td>
<td>0.0064</td>
<td>0.0240</td>
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</tbody>
</table>
Table 2
Modified Hend. and Pabis

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>Moisture ratio(MR)</th>
<th>Drying constant (k)</th>
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<tbody>
<tr>
<td>45</td>
<td>0.351303414</td>
<td>0.223982466</td>
<td>0.351303379</td>
<td>0.906</td>
<td>0.0016</td>
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<tr>
<td>55</td>
<td>0.102436192</td>
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<td>0.102436213</td>
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<tr>
<td>65</td>
<td>0.356359275</td>
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<td>0.356359274</td>
<td>0.975</td>
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<td>75</td>
<td>0.355903807</td>
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<td>0.355904063</td>
<td>0.975</td>
<td>0.00157</td>
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</table>

Two-term Exponential

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>Moisture ratio(MR)</th>
<th>Drying constant (k)</th>
</tr>
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<tbody>
<tr>
<td>45</td>
<td>0.001190524</td>
<td>0.996689027</td>
<td>0.342620508</td>
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<td>0.921</td>
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<td>55</td>
<td>0.209512193</td>
<td>0.979</td>
<td>0.000334</td>
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<td>65</td>
<td>0.32647214</td>
<td>0.979</td>
<td>0.000297</td>
<td>0.005176</td>
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<tr>
<td>75</td>
<td>0.368858097</td>
<td>0.913</td>
<td>0.000713</td>
<td>0.080135</td>
<td></td>
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</tbody>
</table>

NEWTON

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>k</th>
<th>Moisture ratio(MR)</th>
<th>Drying constant (k)</th>
</tr>
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<tbody>
<tr>
<td>45</td>
<td>0.084800268749533</td>
<td>0.923</td>
<td>0.00241</td>
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<td>55</td>
<td>0.209512193495314</td>
<td>0.979</td>
<td>0.00137</td>
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<td>65</td>
<td>0.32647214291968</td>
<td>0.975</td>
<td>0.000297</td>
</tr>
<tr>
<td>75</td>
<td>0.368858097872436</td>
<td>0.913</td>
<td>0.000713</td>
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</table>

4. CONCLUSIONS

In this study, the drying behaviour of *Moringa oleifera* leaves was investigated in a mechanical cabinet dryer with forced convection mode. The following submission are made:

1. Drying air temperature is a significant factor in drying of *Moringa Oleifera* leaves.
2. Higher drying air temperature resulted in a shorter drying time.
3. Drying of the leaves takes place in the falling rate period and there was no constant rate period in most of the dried materials.
4. The diffusion model gave the best for *Moringa oleifera* samples dried at 45 and 55°C while the Simplified Fick’s (SFFD) diffusion was the best model for 65 and 75°C.

5. REFERENCES


