



# Comparative Study of Three Solar Drying Methods of *Adenсонia digitate L.* (Baobab Leaves using Drying Kinetics and Empirical Drying Models)

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## Authors' contributions

This work was carried out in collaboration among all authors. Author SAO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author NO managed the analyses of the study. Author YAU managed the literature searches. All authors read and approved the final manuscript.

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## ABSTRACT

A comparative study of three drying methods of baobab leaves have been conducted and reported. Mixed mode solar drying, indirect mode solar drying and open sun drying of baobab leaves were conducted based on three drying models viz a viz Lewis, Page and Henderson and Pabis models were employed in this research. Baobab leaves dried faster when dried under the mixed mode on-farm solar dryer. Drying time reduced considerably using the mixed mode on-farm solar dryer. Drying data were fitted into Lewis, Page and Henderson and Pabis models. Henderson and Pabis model ( $R^2=0.9999, 0.9611, 0.9656$ ;  $X^2= 1.0297, 0.7931, 0.7710$ ; RMSE= 0.5859, 0.6898, 0.6802 and MBE= -0.4.135, -0.4.231, -0.4176) gave the best prediction for the mixed mode drying). In the same way Henderson and Pabis model ( $R^2=0.7450, 0.7699, 0.8243$ ;  $X^2= 1.9025, 0.4026, 0.2006$ ;

RMSE= 1.0684, 0.5181, 0.4058 and MBE= -0.8966, -0.3823, 0.2789) gave the best prediction for the indirect mode drying of baobab leaves. Effective moisture diffusivity of baobab leaves varied between  $-6.382 \times 10^{-04}$  and  $-1.108 \times 10^{-03} \text{ m}^2/\text{s}$ .

**Keywords:** Drying; solar; baobab leaves; mixed mode dryer; indirect mode dryer.

## NOMENCLATURE

- MSD P1 : 1st tray from bottom in drying chamber of the mixed mode dryer  
 MSD P2 : 3rd tray from bottom in the drying chamber of the mixed mode dryer  
 MSD P3 : 5th tray from bottom in the drying chamber of the mixed mode dryer  
 ISD P1 : 1st tray from bottom in drying chamber of the indirect mode dryer  
 ISD P2 : 3rd tray from bottom in the drying chamber of the indirect mode dryer  
 ISD P3 : 5th tray from bottom in the drying chamber of the indirect mode dryer  
 OSD : Open sun drying

## 1. INTRODUCTION

Baobab tree (*Adansonia digitata* L.) is a massive deciduous tree that grows predominantly in semi-arid region of Africa: from Senegal to Nigeria down to Kenya and all through southern African and Madagascar [1]. It is recorded that some of the trees are 1000 years old. *A. digitata* is an important African tree known for its medicinal and nutritional value. The plant parts i.e leaves, fruit pulp, seed and bark are important in treating diarrhea, microbial infections and malaria [2]. Reports have it that most part of the tree especially the leaves have interesting anti-inflammatory and anti-oxidant properties and as such baobab have been used extensively right from ancient times in local medicine [3]. Just like any other naturally occurring tree, baobab trees produce fresh green leaves during the rainy season which they shed during dry season. In view of these baobab leaves which have been previously identified as a good and affordable source of Vitamin A and C are harvested in large quantities, dried and stored for use during dry season.

Right from time immemorial, drying has remain the major way of preserving agricultural products especially fruits and vegetables which prone to deterioration shortly after harvest. Traditionally on the farm, vegetables are dried by spreading the fresh products on mats, tarred roads or cemented floors. However, this method results in poor quality of dried vegetable products.

Research also shows that drying in general affects the nutritional value of vegetables, leading to a decrease in many phytochemicals, which are of health benefits, resulting in reduction of nutritional quality of the final products [4]. From late 19th century many drying techniques were developed to improve upon the efficiencies of the solar drying systems without having negative impact on the quality of the final dried products [5]. A few examples are mixed, hybrid and indirect solar dryers. A good overview of these dryers and there application can be obtained in the book of Solar Drying by [6].

The mixed mode and indirect mode solar dryers have over the years received maximum attention of researchers especially in thermal performance and mathematical modeling [6]. Despite these, limited work is available in open literature on a direct comparison of these dryers with respect to drying of fruits and vegetables. Previous researches made on mixed mode and indirect mode solar dryer indicates a higher drying rate and lower drying cost with mixed mode dryer compared to the indirect mode dryer [7]. Also higher effectiveness was obtained for mixed mode solar dryer than indirect mode solar dryer [8]. However, when the quality of the final products is of utmost importance, the indirect mode solar dryer can be considered. According to [9], long exposure of the products to ultraviolet radiations from the sun leads to greater loss in quality. Baobab leaves dried under indirect solar dryers was found to have retained more provitamin A compared to baobab leaves exposed to direct sunlight [10]. [11] studied the effects of different drying methods on the nutritional and quality attributes of baobab leaves. The study compared the effects of open sun drying, shed drying, carbinet dryer at 50°C and a mixed mode solar dryer and found shed drying as a better method to use in ensuring high retention of nutrients while maintaining the aesthetic parameters that promotes acceptability of the products in the market. Therefore , this study is aimed compare the drying characteristics and final quality of baobab leaves dried under open sun drying, mixed and indirect mode solar drying.

## 2. MATERIALS AND METHODS

### 2.1 Materials

Fresh Baobab leaves used for this study were obtained from a local market in Zaria, Kaduna State, Nigeria. The leaves were carefully detached from the stem, sorted to remove bad leaves and washed then allowed to drain. Well drained baobab leaves were kept for 6h at room temperature to maintain thermal equilibrium, before the start of the drying process. Initial moisture content of the sample was determined using an electric oven at 105°C for 24h. Initial moisture content of the baobab leaves was 64% wet basis. Three portions of the baobab leaves were subjected to three drying methods namely mixed mode solar drying, indirect mode solar drying and open sun drying.

During each run, sample leaves were placed in a single layer on drying trays arranged in the drying chambers of the mixed mode and indirect mode solar dryers. While for open sun drying, sample leaves were placed in single layers on a cemented surface. Monitored parameters include: sample temperature, sample weight, relative humidity and temperature (ambient, drying chamber, collector inlet and outlet). Drying was concluded when a moisture content of 9.5% (w.b) was achieved.

### 2.2 Baobab Drying Process

Three different drying tests were carried out under similar experimental and climatic conditions. These test includes, baobab leaves dried under mixed mode solar dryer, indirect mode solar dryer and open sun drying. Under mixed mode dryer, baobab leaves are subjected to both direct solar radiation and heat from the collector, as such the effect of direct solar radiation will have effect on the drying process as well as the final dried products. However, baobab leaves in the indirect mode dryer are subject only to heat from the collector, in this case the effect of direct solar radiation is mitigated. Nine (9) experimental runs were conducted, with each run having 500g  $\pm$  20g of fresh baobab leaves. 1h into the drying experiment, change in weight was measure and recorded, subsequently, change in weight was measure at 30min intervals until there was no change in weight for two consecutive readings. Each test was repeated 3 times and the average of the three readings was noted and recorded.

### 2.3 Drying Methods

Pictorial views of the mixed mode and indirect mode solar dryers used for the drying process are presented in figures 1a 1b and 1c. Fresh baobab leaves to be dried are spread on the trays within the drying chamber of these dryers. In the mixed mode dryer, products to be dried are subject to direct solar radiation as well as heat from air heated by the solar collector. In the indirect mode dryer, fresh baobab leaves are enclosed in a cabinet, making it impossible for direct solar radiation to heat the baobab leaves while drying. In this case the baobab leaves are only subjected to heat from air heated by the collector. Heated air is blown over the baobab leaves with the aid of an axial fan placed at the end of the collector.

### 2.4 Color Analysis

Fresh and dried baobab leaves were grounded and mixed with little distilled water. Under a standard color temperature of 5500k, the products were photographed in closely monitored conditions using a Panasonic digital LUMIX TS7 camera and light box (Sanoto Box 16 x 12 in) using standard procedures as outlined by [12]. Adobe Photoshop 7 in a computer system was used to determine the corresponding coordinates. a\*coordinate which ranges from green (-a) to red (+a), L\* coordinate which ranges from 0 (black) to 100 (white), and b\* coordinate ranging from blue (-b) to yellow (+b). The reading was performed grounding the baobab leaves into powder before taking the readings. Triplicate measurement where taken and means of the three readings were noted and recorded.

### 2.5 Modelling of Drying Curves

Drying models in recent times have gained wide acceptance for analytical drying purposes, designing new and simulating existing drying systems. Researchers have employed exponential drying models; Newton (Lewis), Page, Henderson and Pabis, Parabolic, logarithmic and Wang and Singh models in describing the drying characteristics of various agricultural materials. Simplifying the general series of Fick's 2nd law of diffusion gives these equations.

a. *Newton (Lewis) model*: an exponential model is the solution of Fick's law, with the assumptions of negligible shrinkage, diffusion based moisture

migration, temperature, and constant diffusion coefficients. Lewis is one of the simplest models in describing movement of moisture in agricultural products. It has been successfully used in the drying characteristics of Grape seeds [13], Red chili [14] and strawberry [15].

$$MR = e^{-kt} \quad (1)$$

b. *Henderson and Pabis model*: this is a solution of general series of Fick's second law which has been used to describe the drying behaviour of African breadfruit seed [8] and mango and cassava [2] successfully.

$$MR = ae^{-kt} \quad (2)$$

c. *Page model*: this is a modification of the Newton's model to remove the shortcomings associated with Lewis model. Here we see the introduction of an empirical constant (n) to the time term. It was successfully used to describe the drying characteristics of tomato [3], and barberries [16].

$$MR = e(-kt^n) \quad (3)$$

In the proposed models discussed earlier, a, b, c and n are drying coefficients and k is the drying constant given in (/min). Table 1 shows the drying models;



**Fig. 1a. Axial Fan Connected to the dryers**



**Fig. 1b. Mixed mode on-farm solar dryer**



**Fig. 1c Indirect mode on-farm solar dryer**

**Table 1. Mathematical models fitted to various fruits and vegetables**

s/no	Model	Model Equation	References
1	Newton (Lewis)	$MR = e^{(-kt)}$	[15] El-Beltagy et al. 2007, [14] Hossain et al. 2007, [17] Roberts et al. 2008.
2	Henderson and Pabis	$MR = ae^{(-kt)}$	[2] Koua et al. 2009, [8] Shittu and Raji 2011
3	Page model	$MR = e(-kt^n)$	[3] Doymaz 2007, [16] Aghbashlo et al. 2009

Coefficient of determination ( $R^2$ ) was employed to ascertain the suitability of each drying model. Other statistical tools used are; Chi square ( $X^2$ ), root mean square (RMSE) and mean bias error (MBE).  $R^2$  value must be highest while MBE,  $X^2$  and RMSE values lowest for a quality fit [18].

$$RMSE = \left\{ \frac{1}{N} \sum_{i=1}^N ((MR_{(exp,i)} - MR_{(pred,i)})^2) \right\}^{\frac{1}{2}} \quad (4)$$

$$MBE = \left\{ \frac{1}{N} \sum_{i=1}^N ((MR_{(pred,i)} - MR_{(exp,i)}) \right\} \quad (5)$$

$$X^2 = \frac{\sum_{i=1}^N (MR_{(exp,i)} - MR_{(pred,i)})^2}{N - Z} \quad (6)$$

## 2.6 Determination of Effective Moisture Diffusivity

Movement of water during drying process is described using the fick's law of diffusion model. It provides a description of the average diffusion coefficient for the whole drying process. The solution to the equation developed by [19] can be expressed in logarithmic form for a long period drying as [18];

$$MR = \frac{8}{\pi^2} \exp \left[ \frac{D_{eff}}{4L^2} \pi^2 t \right] \quad (7)$$

Where;  $D_{eff}$  is moisture diffusivity ( $m^2/s$ ),  $L$  is half the thickness of sample ( $m$ ) and  $t$  is drying time ( $s$ ). The slope of  $\ln(MR)$  against time at different temperature gives the effective moisture diffusivity.

$$\text{Slope} = \frac{D_{eff}}{4L^2} \pi^2 \quad (8)$$

## 3. RESULTS AND DISCUSSION

### 3.1 Drying Curves for Baobab Leaves under the Three Drying Methods

Fig. 2. shows the relationship between moisture content and drying time of baobab leaves subjected to mixed mode solar, indirect mode solar and open sun drying. It can be established

from the figure, that moisture content for all samples decreased continually as drying time proceeds. Time required in reducing baobab leaves to 6.5% moisture content ranged from 10 to 24h in the mixed mode dryer, 28 to 31h in the indirect mode dryer and 28h under open sun drying. Generally drying process involves the removal of both free moisture and later bound moisture from the interior of the food product till a final limit is reached under constant and falling rate drying periods. However in leaves, the unbound (free moisture) is insignificant, hence the relative low drying time of leafy vegetables when compared to tomatoes, okra and potatoes [20]. As observed in Fig. 2, from all the drying curves of all the drying methods, more moisture is removed during the constant rate which lasted for about 5h, 10h, 15h and 18h for MSDP1, MSD P2 & P3, ISDP1 and OSD, and ISDP2&P3 respectively. During the remaining part of the drying process (falling rate period), more time was required to remove smaller amount of moisture, consequently, this period determined the overall drying time of the baobab leaves. It can be seen that baobab leaves under open sun dried faster those leaves under ISD P2 and ISD P3, as rewetting of the leaves occurred during the night periods, which is more in the ISD than under open sun. Interestingly, [10] obtained lower drying time of 7h – 9h when baobab leaves were dried under open sun and shade drying, in this case elements of weather such as ambient air, relative humidity and wind velocity played a significant role in enhancing the overall drying process.

In Table 2, drying time was reduced by 64.43% and 14.29 % when baobab leaves were dried in the mixed mode on-farm solar dryer. However, drying time was not much affected when the leaves were dried under the indirect mode solar dryer. In general, the time required to reduce the moisture content to any given level is dependent on the drying conditions, and this is lowest when the baobab leaves were dried in tray 1 of the mixed mode on-farm solar dryer.

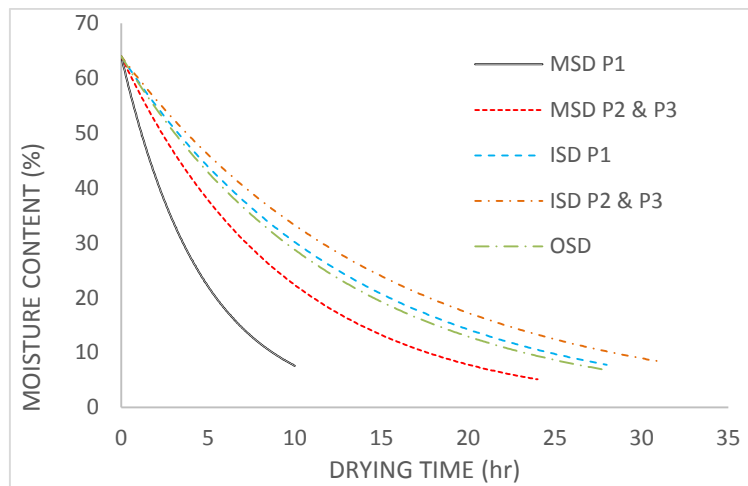


Fig. 2. Drying rate of Baobab leaves under MSD, ISD and OSD

Table 2. Effect of different drying methods and drying tray position on drying time of baobab leaves

Drying treatment /Tray Position	Time (h)	Percentage reduction in time (%)
OSD	28	0.00
Mixed mode on-farm solar dryer		
P1	10	64.43
P2	24	14.29
P3	24	14.29
Indirect mode on-farm solar dryer		
P1	28	0.00
P2	31	-10.71
P3	31	-10.71

### 3.2 Modeling of Drying Curves

The experimental data were fitted with three drying models as shown in Table 3. The results obtained for the non-linear regression of the models which includes the criteria for selecting the goodness of fit, i.e, coefficient of determination ( $R^2$ ), reduced chi-square ( $X^2$ ), root mean square error (RMSE), mean bias error (MBE) and the constants of these equations are presented in Tables 3 and 4. The ranges of values.

Considering MSD dried baobab leaves, Henderson and Pabis model having highest value or  $R^2$  in MSDP1 (0.9999), MSDP2 (0.9611) and MSDP3 (0.9656) than both Lewis and Page models best fits the drying characteristics of baobab leaves under MSD. However, considering the model with the lowest values  $X^2$ , RMSE and MBE, Lewis model having  $X^2$  values (0.0107, 4.2E-05, 2.6E-05), RMSE values (0.0597, 0.0050, 0.0039) and MBE values (-0.0445, 0.0028, 0.0018) for MSDP1, MSDP2 and

MSDP3 respectively best fitted to the dimensionless moisture content data.

Moreover, considering baobab leaves dried under ISD, Henderson and Pabis model having the highest values of  $R^2$  in ISDP1 (0.7450), ISDP2 (0.7699) and ISDP3 (0.8243) than the  $R^2$  values of Lewis and that of Page best fits the drying behavior of baobab leaves under the ISD. Main while, considering the model with the lowest  $X^2$ , RMSE and MBE value, Lewis Model having  $X^2$  values (0.0207, 0.0067, 0.0067), RMSE values (0.1113, 0.0677, 0.0689) and MBE values (0.0369, -0.0473, 0.0482) for ISDP1, ISDP2 and ISDP3 respectively best fitted to the dimensionless moisture content data.

Considering the OSD dried baobab leaves, Page model having the highest value of  $R^2$  (0.8331) than that of Lewis and Henderson and Pabis models best describes the drying characteristics of Baobab leaves under OSD. However considering the models the lowest values of  $X^2$ , RMSE and MBE also Lewis model with  $X^2$

(0.0024), RMSE (0.0338) and MBE (0.0193) best fitted the moisture content data of baobab leaves. Based on the results, Henderson and Pabis model is selected as the suitable model to predict the mixed mode solar drying and indirect mode solar drying of baobab leaves while Page model is selected as the suitable model to predict the open sun drying of Baobab leaves. In a similar research on baobab leaves by [10] Henderson and Pabis Model had the highest.

### 3.3 Effective Moisture Diffusivity

$D_{eff}$  was determined using the method of slopes from eq. (8). The values of  $D_{eff}$  of baobab leaves samples varied between  $-6.382 \times 10^{-04}$  and  $-1.108 \times 10^{-03} \text{m}^2/\text{s}$ . The  $D_{eff}$  values obtained for ISDP1 was the least ( $-6.382 \times 10^{-04} \text{m}^2/\text{s}$ ) while that of the open sun drying was the highest ( $-1.108 \times 10^{-04} \text{m}^2/\text{s}$ ) which indicates that  $D_{eff}$  is a function of temperature and air velocity. Diffusion is the major means Moisture transport within a product during drying. Here the drying temperature and air speed has a significant effect on mass transfer of moisture especially from leaf surface, hence open sun drying resulted in higher moisture diffusion than the indirect mode and the mixed mode dryer. The effective moisture diffusivity obtained for tomatoes and okra is similar to that obtained for apples [21].

### 3.4 Color of Fresh and Dried Baobab Leaves

The color of MSD dried, ISD dried, OSD dried, and fresh samples of baobab leaves are presented in Table 5. Color change is observed in all the samples, this indicates that drying has a significant effect on the physical appearance of baobab dried leaves. These color changes are due to direct and long exposure of the products to solar radiation and also due to some changes in the chemical properties of the dried leaves. These changes in chemical properties that leads to color changes is mainly due to carotenoids degradation and oxidation of chlorophyll pigment of greens. Sugar content, amino acids and processing time have also been reported to affect the color of dried vegetables by causing formation of brown pigments [22]. After drying an increase in brightness i.e increase in  $L^*$  of baobab leaves, there was also increase in redness ( $a^*$ ) and yellowness ( $b^*$ ). This results indicates that baobab leaves became brownish. The increase in brightness was more in ISD but browning was lesser ( $L^*=39.93$ ,  $a^*=5.42$ ,  $b^*=12.50$ ). Whereas Baobab leaves under MSD is darker and more brownish ( $L^*=37.20$ ,  $a^*=9.47$ ,  $b^*=15.20$ ) compared to ISD. Baobab leaves became more brownish when compared to ISD and MSD ( $L^*=38.20$ ,  $a^*=9.67$ ,  $b^*=12.50$ ). This result agrees with the findings of [11].

**Table 3. Statistical results obtained in the modeling of the drying data**

Model	Drying Condition	R <sup>2</sup>	CHI	RMSE	MBE
Lewis	MSDP1	0.7371	0.0107	0.0597	-0.0445
	MSDP2	0.7488	4.2E-05	0.0050	0.0028
	MSDP3	0.7583	2.6E-05	0.0039	0.0018
	ISDP1	0.7023	0.0207	0.1113	0.0369
	ISDP2	0.6023	0.0067	0.0677	-0.0473
	ISDP3	0.7558	0.0067	0.0689	-0.0482
	OSD	8.0197	0.0024	0.0338	0.0193
	Henderson and Pabis	MSDP1	0.9999	1.0297	0.5859
MSDP2		0.9611	0.7931	0.6898	-0.4231
MSDP3		0.9656	0.7710	0.6802	-0.4176
ISDP1		0.7450	1.9025	1.0684	-0.8966
ISDP2		0.7699	0.4026	0.5181	-0.3823
ISDP3		0.8243	0.2306	0.4058	-0.2789
OSD		0.8223	1.0929	0.8098	-0.6015
Page		MSDP1	0.9234	1.1894	0.6296
	MSDP2	0.9224	0.2258	0.3681	0.3239
	MSDP3	0.9217	0.2189	0.3624	0.3189
	ISDP1	0.5144	0.7889	0.6880	0.6084
	ISDP2	0.5607	0.0139	0.0913	0.0244
	ISDP3	0.6345	0.0104	0.0833	0.0203
	OSD	0.8331	0.2566	0.4136	0.3349

for R<sup>2</sup>, X<sup>2</sup>, RMSE and MBE are 0.3450 to 0.9999, 2.6E-05 to 1.9025, 0.0050 to 1.0684 and -0.8966 to 0.5128 respectively for baobab leaves. Selection of best model to fit in the drying data of baobab leaves is based on the model with highest R<sup>2</sup> value and lowest X<sup>2</sup>, RMSE and MBE values

**Table 4. Equation constants for the drying models**

Model	Drying Condition	n	a	k
Lewis	MSDP1			0.5848
	MSDP2			0.3473
	MSDP3			0.3460
	ISDP1			0.1926
	ISDP2			0.1927
	ISDP3			0.2018
	OSD			0.2272
Henderson and Pabis	MSDP1		0.0050	0.4165
	MSDP2		-0.4745	0.2577
	MSDP3		-0.4537	0.2577
	ISDP1		-0.9386	0.0749
	ISDP2		-0.0573	0.1421
	ISDP3		0.1068	0.1644
	OSD		-0.6005	0.1300
Page	MSDP1	0.5140		0.0478
	MSDP2	0.6043		0.1826
	MSDP3	0.6025		0.1861
	ISDP1	0.3021		0.0345
	ISDP2	0.4440		0.4707
	ISDP3	0.5302		0.5708
	OSD	0.4145		0.1651

value of  $R^2$  but was chosen as the best fit because of its high value of  $X^2$ , RMSE and MBE, when compared with Page model. Henderson and Pabis model have also been used to successfully describe the drying characteristics of Apple slices [23]

**Table 5. Colour values of msd, isd, osd dried and fresh baobab leaves**

Drying method	L*	a*	b*
Fresh	29.00	-7.50	5.6
MSD	37.20	9.47	15.20
ISD	39.93	5.42	12.50
OSD	38.20	9.67	16.40

#### 4. CONCLUSION

Drying characteristics of baobab leaves were investigated under a mixed mode on-farm solar dryer, indirect mode on-farm solar dryer and open sun drying. Drying time was significantly reduced in the mixed mode on-farm solar dryer than in the indirect mode on-farm solar dryer. The mixed mode dryer reduced the drying time of baobab leaves by 64.43%. Henderson and Pabis model gave the best fit to predict the mixed mode and the indirect mode on-farm solar drying of baobab leaves. Reduction in drying time and quality of color retention makes the mixed mode and indirect mode on-farm solar dryers a good option for drying of baobab leaves on the farm.

#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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