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Drying moringa leaves and flowers using a tunnel dryer: experimental study and modeling of drying kinetics

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ABSTRACT

This work highlights the use of an indirect trapezoidal tunnel solar dryer for moringa drying. We sampled moringa leaves and flowers harvested in the Dakar region. Tests were carried out over two days, between 11 a.m. and 4 p.m. under real conditions. Drying conditions varied from an average irradiance of 530 W/m² on the first day to 700 W/m² on the second. The average air temperature inside the dryer varied from 35°C on the first day to 49.5°C on the second. Mass loss results obtained by weighing showed a more rapid variation in mass loss for leaves than for flowers. We plotted experimental curves of reduced water content against drying time, approximating them using empirical or semi-empirical models from the literature. Model selection criteria were defined, and the Page and logarithmic models gave correlations of 0.99859 and 0.96463, respectively. The effective diffusivity (D_{eff}) for both products was evaluated by fitting experimental data to the Crank diffusion equation. Expressed in terms of the logarithm of reduced moisture, the following D_{eff} values were obtained:

Leaves: D_{eff} ranged from $8.12135.10^{-10}$ to $9.16675.10^{-10}$ m²/s.

Flowers: D_{eff} ranged from $1.38899.10^{-9}$ to $1.41385.\ 10^{-9}$ m²/s.

These values indicate the rate at which moisture diffuses through the plant material under the specific conditions of the experiment.

Nomenclature
X = water content (g water / g dry matter);
t = time (s);
L = sample thickness (m);
D_{eff} = diffusion coefficient (m^2 / s).
$M_{h(t)}$: Wet mass of fresh product considered

I. INTRODUCTION

Drying is one of mankind's oldest preservation techniques, used to reduce the moisture content of various products. It is used in many fields, notably in the food industry. For the most part, this drying is carried out freely in the sun or shade, which can pose a hygiene problem.

Unlike other products, the leaves are more sensitive. So one way to consume Moringa oleifera leaves is to dry and powder them, making them easy to store and incorporate into dishes at any time. To ensure good nutritional and sanitary (microbiological) quality of the leaf powder, its residual moisture content should not exceed 7.5%, the drying time should be as short as possible, and the drying temperature should not be too high (50-55°C maximum). Even if a high proportion of the vitamins are lost during drying, leaf powder is still a very rich nutritional supplement, as it is a leaf concentrate [1].

Moringa is considered to be a product of great nutritional, traditional and medicinal value.

The nutritional value of Moringa leaves is of a richness rarely observed. In fact, the leaves also contain a complex of B vitamins, iron, calcium, proteins, zinc, selenium and, quite unusually for a plant, all 10 amino acids essential for human beings. [2]

The work of Emelike et al, 2016 [3] carried out under three drying modes (oven, sun, shade) to study the effect of drying on immediate and mineral properties.

This work showed that there was no significant effect ($p < 0.05$) in the magnesium content of the samples, whereas there was in the calcium, iron and zinc content. The oven-dried sample had the highest calcium (190.5 mg / 100 g), sun-dried the highest zinc (7.1 mg / 100 g) and shade-dried the highest iron content at 51.3 mg / 100 g.

Ademola K. Aremu's [4] work on moringa seed drying kinetics involved studying the performance of an appropriate mathematical model. This performance was investigated by comparing the experimental and predicted coefficient of determination and root mean square error of the moisture ratio using non-linear analysis. This is the subject of our study for moringa flowers and leaves.

The work of M. A. Ali [5] on modeling the drying kinetics of moringa leaves (kiln-dried) revealed that the mathematical model with the best fit of the drying curves was that of Page for maximum and minimum values (0.998 to 0.999 and 0.0008 to 0.0002) of r^2 and χ^2 respectively. Kiln-drying at 40°C also revealed optimum color values with 4.77% moisture content after 8h drying time.

This dry-base moisture content at an instant t is defined by the final moisture content is a characteristic of each product. It is the optimum value for which the product does not deteriorate and retains its nutritional and organoleptic qualities (shape, texture, color, odor and essential oils) [6].

Based on these studies, we are carrying out a scientific study of the drying of moringa leaves and flowers using an indirect trapezoidal tunnel dryer with forced convection. To observe the influence of drying temperature on drying kinetics, to select a suitable model for this drying process using empirical models from the literature, and to determine the effective diffusivity of moringa leaves and flowers.

II. THEORETICAL ANALYSIS

II-1. Variation in water content, dry basis

It consists in monitoring the wet mass $M_h(t)$ of the product to be dried as a function of time, by successive weighings until a constant value is reached. Thus, the final mass m_s is obtained after 24 hours in an oven at 102°C. [6]

$$X(t) = \frac{m_{h(t)} - m_s}{m_i} \tag{1}$$

II-2. Determining equilibrium content

The mass of each sample is measured regularly, enabling the equilibrium water content to be determined using the following relationship [7]:

$$X_e = \frac{m_{eq} - m_s}{m_s} \tag{2}$$

Where Xe is the equilibrium water content, m_{eq} is the equilibrium sample mass and m_s is the anhydrous mass.

II-3. Reduced humidity

This is the ratio of the variation in moisture content at time t and the equilibrium moisture content to the ratio of the variation in initial moisture content and the equilibrium moisture content given by equation (3).

$$X_r = \frac{X(t) - X_e}{X_c - X_e} \tag{3}$$

III. Mathematical model

Several empirical or semi-empirical models are used to describe drying kinetics and predict reduced water content X_r as a function of drying time for moringa leaves and flowers. These models are defined in Table 1 [8, 9, 10]. This smoothing was performed using the Levenberg-Marquard non-linear regression method on origin pro-9.1.

Table 1. Mathematical models

Number	Model name	Expression
1	Newton	$X_r = \exp(-kt)$
2	Page	$X_r = \exp(-kt^n)$
3	Logarithmic	$X_r = a\exp(-kt) + c$
4	Wang and Singh	$X_r = 1 + at + bt^2$
5	Two-term	$X_r = a\exp(-kt) + b\exp(-gt)$

Non-linear least-squares regression was used to evaluate model parameters. Goodness of fit was determined using statistical parameters, (r^2, RMSE, χ^2).

These parameters can be described in the following equations:

Correlation coefficient (r^2) given by equation (4) [11]

$$r^2 = \frac{\sum_{i=1}^{N}\left(X_{rpre,i} - X_{r\exp,i}\right)^2}{\sum_{i=1}^{N} X_{r\exp,i}^2} \tag{4}$$

Roots mean systematic error (RMSE) defined by equation [12] (5).

$$RMSE = \frac{1}{N}\sum_{i=1}^{N}\left(X_{rpre,i} - X_{r\exp,i}\right) \tag{5}$$

χ^2 -reduced square given by equation (6). [13]

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(X_{rpre,i} - X_{r\exp,i}\right)^2}{N - Z} \tag{6}$$

Where $X_{r,pre,i}$ is the predicted relative humidity, $X_{r,\exp,i}$ the experimental relative humidity, and Z is the number of constants for each regression model.

IV Determining the effective diffusion coefficient

The effective diffusivity is determined from Fick's Law of Moisture Transfer [10]. It is defined by equation [7].

$$\frac{\partial X}{\partial t} = D_{eff}\nabla^2 X \tag{7}$$

The solution of the equation is given by Crank in one dimension [8].

$$X_r = \frac{8}{\pi^2}\sum_{j=0}^{\infty}\frac{1}{(2j-1)^2}\exp\left[-(2j-1)^2\frac{\pi^2 D_{eff} t}{L^2}\right] \quad (8)$$

With L the thickness of the product
Since the drying time is long, the other terms of the series can be neglected in front of the first term. This leads us to equation (9).

$$X_r = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff} t}{L^2}\right) \quad (9)$$

The effective diffusivity is obtained by making the logarithm of the reduced humidity given by equation (10).

$$\ln(X_r) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff} t}{L^2} \quad (10)$$

With D_{eff} which is determined using the slope of the experimental results.
The result is a straight line of slope $D_{eff}\pi^2/L^2$ which allows calculation of the effective diffusion coefficient typically determined as follows:[11]

$$D_{eff} = -\frac{KL^2}{\pi^2} \quad (11)$$

V. Materials and methods

V.1 Experimental set up

We have a mixed tunnel dryer consisting of a 50 WC 12volt photovoltaic module, two 12-volt 1.3 A fans. A 1.5m² absorber and a 2m² drying cabin with four horizontal racks on the same level. Solar radiation arriving at the surface of the dryer is converted into electricity at the module to drive the fans, which send the air to the absorber, which is responsible for storing heat that it will transfer to the fluid. This heat-laden fluid enters the cabin to dry the wet products before being evacuated through the dryer outlet (fig.1.). The products are arranged horizontally inside this cabin (fig.2.).

Fig.1. indirect dryer.

Fig.2. Internal view of the drying chamber.

To carry out our various measurements, we will use the following instrumentation:
- **Oven:** to determine the anhydrous mass of the fish
-**Thermochons:** these are button-sized stainless-steel devices that can be placed directly in your test environment without the need for external probes.
-**Thermocouple**: for measuring ambient and dryer interior temperature
- **Precision scale:** for weighing samples

Table 2: measuring instrument specifications

Designation	Model	Measurement range	Precision
Thermochrons	DS1922T	0 to 125°C	0.5°C à 0.0625°C
Thermocouple	PCE-T390	100 to 1370°C	0.2 %
Solarimeter	PYR13O7	0 to 1999W/m²	±5 %
Precision scale	CX 265	0 to 60g	0.01mg
Oven	BINDER	0 to 250°C	-

V.3 Experimental procedure

The tests were carried out at CERER (Center for Study and Research on Renewable Energies) during the month of January. Fresh moringa leaves were picked from the same study site, because of the presence of the plant. The physical quality of the product (color, texture, etc.) was checked. Basins are used for trimming, i.e. washing in ordinary water. The product undergoes no pre-treatment. Other equipment was used to ensure that our drying procedure was properly followed, including.
-Thermochrons, which are placed in contact with the product at various points (rack, product, absorber, glass). These probes instantly record the temperature of the product to which they are attached, as well as the time. Software can be used to retrieve all the data recorded by these probes during tests.
-Thermocouples record temperatures inside and outside the dryer.
Solarimeter: to measure the intensity of sunshine at the study site.
A desiccator for transporting samples to the measurement site, to avoid re-wetting the product.
We chose 4 samples, including 2 Moringa flowers and 2 leaves, as controls on the racks and in the dryer. Weighing

was carried out before the start of drying, then during drying at 1-hour intervals. At the end of drying, the samples are placed in a study at a temperature of 102°C for 24 hours. The final product is then weighed to determine the anhydrous mass of the samples.

VI. Results and discussion

Fig.3 and 4 show the variations in relative humidities on a dry basis for the different moringa samples: for the flowers, and the leaves. We observe a more rapid evolution of the drying rate for the leaves than for the flowers. This is explained by the fact that the leaves are thin, which facilitates water migration, whereas the flowers are thicker and contain fibers that prevent rapid drying. We note the unique presence of the slow-down phase, and the absence of the warm-up and constant speed phases, for both leaves and flowers. The water content of flowers decreases with drying time, from 5.5 to 2.1 kg of water/kg of material for flower 1 and 3.5 to 1.5 kg of water/kg of material for flower 2, and slows down between 6 and 8 h of drying time, from 2.1 to 1.2 and 1.5 to 0.5 kg of water/kg of dry material respectively (fig. 3). Similarly, for the leaves, the water content fell with increasing drying time, varying from 3.5 to 0.3 kg water/kg dry matter for the three leaves during the 6h drying time, and slowed down in 2h to reach its equilibrium content for the three leaves at 0.1 kg water/kg dry matter (fig.4).

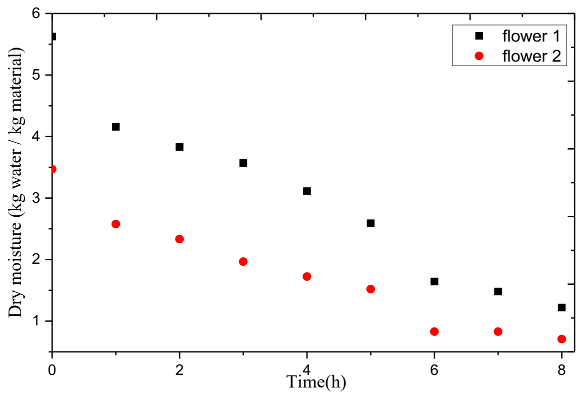

Fig.3. Variation in moringa flower moisture as a function of time

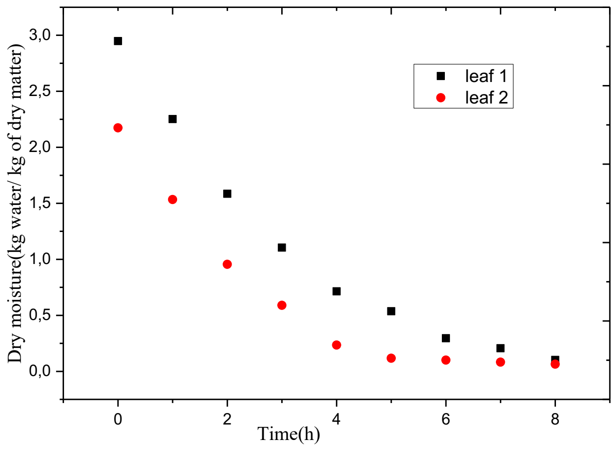

Fig.4. Moisture content of moringa leaves as a function of time

VI.1. Effect of drying air temperature on drying of moringa flowers and leaves

We have plotted the evolution of temperature and humidity as a function of time for moringa leaves (Fig.5) and flowers on the same figure (Fig.6). In both figures, we can see that humidity decreases as temperature increases. We can see that on the first day of drying, temperatures ranged from 25°C to 45°C, with much of the moisture diminishing after five hours of drying. On the second day of drying, there was a slowdown to stabilization, despite the fact that the temperature had reached 50°C.The first observation corresponding to the very rapid drying of the product can be explained by the phase of removal of its free water. Indeed, the product's free water is water whose water activity (a_w) is equal to 1, and drying consists of isenthalpic evaporation of the water. The slow reduction in humidity is reflected in the phase of bound water removal. We note that in a moist product, water is found under three types of bonds (free, weakly bonded and strongly bonded). These bonds, which are very difficult to break, explain the slower drying speed.

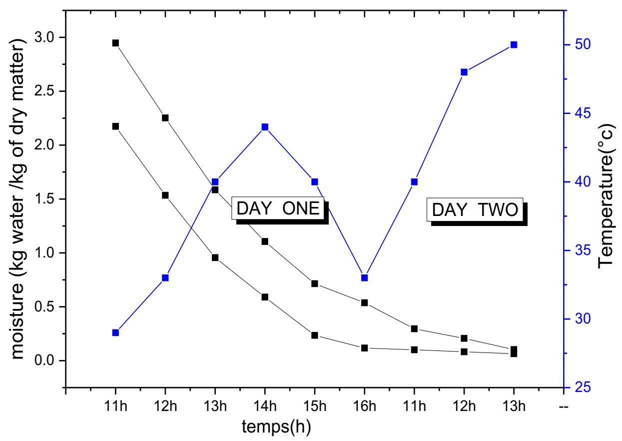

Fig.5 Influence of temperature on flower drying

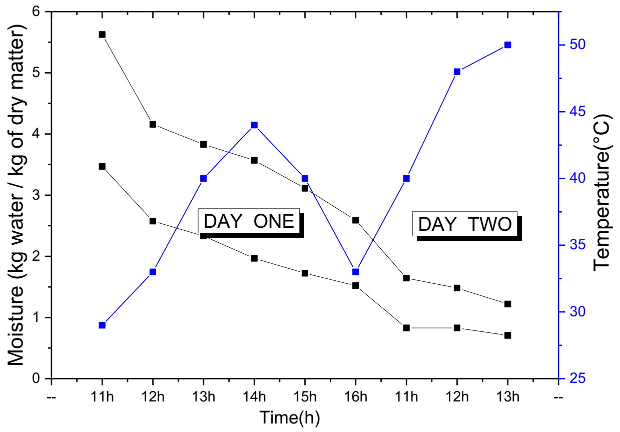

Fig.6 Influence of temperature on leaves drying

VI.2. Modeling drying kinetics

Reduced moisture was plotted against time under the same drying conditions for moringa leaves and flowers. The experimental data obtained were fitted by six empirical or semi-empirical models selected from the literature using the Levenberg-Marquardt non-linear regression method on Origin pro-9.1. Model constants and statistical results are shown in Table 3.

The values of the correlation coefficient (r^2), of and the systematic mean values (RMSE) of the five models shown in Table 3 enabled us, using the selection criteria set out in paragraph III,, to choose the page model for moringa leaves, which gave a good fit with r^2=0.99859 and RMSE=0.00117, χ^2=1.67755.10^{-4}. For flowers the Logarithm model gave the best prediction with r^2 =0.96463 and χ^2 =0.00332, RMSE= 0.01833

Table 3 : Model parameters and statistical results for Moringa leaves and flowers

Model	Samples	Coefficient	r^2	RMSE	χ^2
Newton	Leaf 1	k= 0.35375	0.98922	0.01024	0.00128
	Leaf 2	k= 0.47421	0.98268	0.01775	0.00222
	Flower1	k=0.17805	0.95738	0,02254	0.00282
	Flower2	k= 0.30288	0.94881	0.04579	0.00572
Page	Leaf 1	k= 0.27002 n= 1.22309	0.99859	0.00117	1.67755.10^{-4}
	Leaf 2	k=0.33913 n= 1.35009	0.99717	0.00254	3.62777.10^{-4}
	Flower1	k=0.18739 n= 0.96747	0,95165	0.02238	0.0032
	Flower2	k=0.25034 n=1.13818	0.94631	0.04202	0.006
Logarithm	Leaf 1	a=1.12519 k=0.28535 c= -0.11154	0.99783	0.00154	2.5748.10^{-4}
	Leaf 2	a=1.08922 b=0.41775 c= -0.06347	0.98731	0.00975	0.00163
	Flower1	a=0.42251 b=0.0916 c= -0.47614	0.95567	0.01759	0.00293
	Flower2	a=0.00293 b= 0.01759 c= 0.95567	0.96463	0.02373	0.00395
Wang And Singh	Leaf 1	a=-0.25918 b= 0.01729	0.99645	0.00295	4.20933.10^{-4}
	Leaf 2	a=-0.32399 b= 0.02564	0.99234	0.00687	9.8148.10^{-4}
	Flower1	a=-0.15044 b= 0.00659	0.95024	0.02303	0.00329
	Flower2	a= -0.21412 b= 0.01118	0.96175	0.02994	0.00428
Two-Term	Leaf 1	a= 0.51785 b= 0.51785 g=0.36551 k= 0.36551	0.98563	0.00853	0.00171
	Leaf 2	a=2.00552. 10^6 b= 2.00552.10^{-4} g=5502.9286 k=5558.8972	0.97517	0.0159	0.00318
	Flower1	a=0.48639 b=0.48639 g= 0.17148 k= 0.17147	0.93565	0.02127	0.00425
	Flower2	a=0.50099 b= 0.50099 g=0.3035 k=0.30342	0.9181	0.04578	0.00916

VI.3. Effective moisture diffusion

Figure 7 and 8 shows the variations in the logarithm of the different reduced humidities of the flower and leaf samples as a function of time. We obtain slopes with directing coefficients of $\left(\frac{\pi^2 D_{eff} t}{L^2}\right)$ for all samples Fig.6.and 7

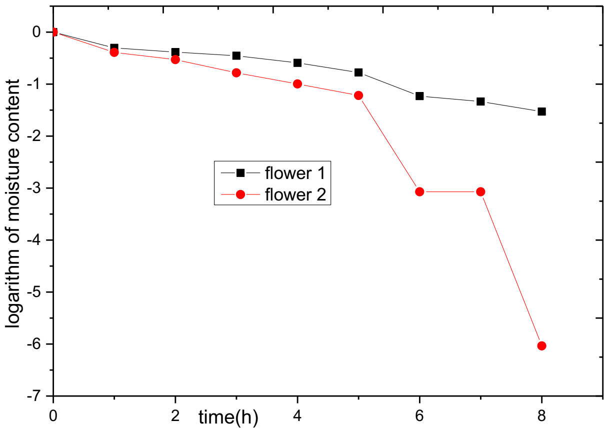

Fig 7. Moringa flower

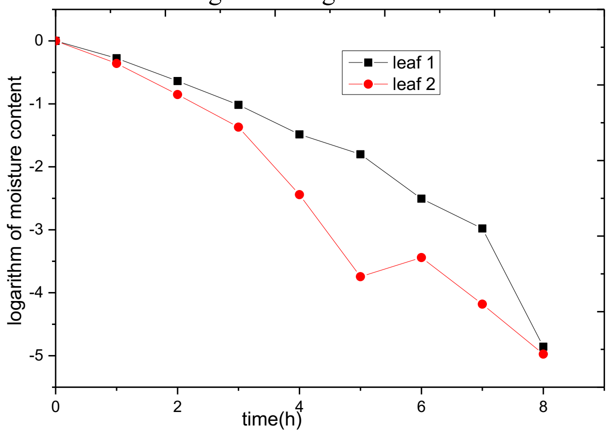

Fig. 8. Moringa leaf

The results of the effective diffusion coefficient D_{eff} for different samples of moringa leaves and flowers are presented in Table 4. D_{eff} coefficients range from $2.31039.10^{-10}$ to $5.21518.10^{-10}$ for leaves and $7.75426.10^{-9}$ to $8.17416.\ 10^{-9}$ for moringa flowers. This shows a higher diffusivity for flowers than for leaves. These results fall within the diffusivity range between 10^{-8} and 10^{-12} found in the literature for leaf drying [10], and for food products [14, 15, 16].

Table 4: Values of effective diffusivity coefficients for different samples

Types	samples	Effective diffusivity	thickness (cm)
Leaf	**Leaf 1**	$5.21518.10^{-10}$	0.001
	Leaf 2	$2.31039.10^{-10}$	0.001
Flower	**Flower 1**	$7.75426.\ 10^{-9}$	0.2
	Flower 2	$8.17416.\ 10^{-9}$	0.5

VII. CONCLUSION

The trapezoidal solar tunnel dryer allowed for the drying of moringa leaves and flowers. The drying conditions showed maximum temperatures of 45°C and 50°C around 1:00 PM on the first and second days, respectively, while the ambient temperature reached 30°C and 32°C at the same time. On average, the dryer reduced the water content of Moringa flowers and leaves from an initial value of 5.5 kg and 3.5 kg of water per kg of dry matter to a final water content of 1.5 kg and 0.3 kg of water per kg of dry matter, respectively, in approximately 8 hours. The study of the solar drying kinetics of moringa leaves and flowers revealed a unique deceleration phase and the absence of the heating and constant temperature phases. The Page and Logarithm models were selected as the most appropriate for describing the drying of leaves and flowers, respectively. The diffusivities of the different samples were uniform, ranging from 10^{-9} for the flowers to 10^{-10} for the leaves. Overall, the trapezoidal solar tunnel dryer saved 33% of drying time compared to shade drying.

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