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Kinetics of Drying Medicinal Plants by Hybridization of Solar Technologies

Margarita Castillo Téllez, Beatriz Castillo Téllez,
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Abstract

Historically, medicinal plants have always had an important place in medicine. Medicinal plants processing represents a great challenge, due to their compounds sensitive to the environmental conditions that surround and degrade them. Mostly of these plants require to be dry to preserve its safety and medicinal properties; therefore, for proper drying, it is necessary to use sustainable devices that protect the desirable characteristics of plants from direct radiation. In this work, the kinetics of dehydration of three medicinal plants are presented in an indirect solar dryer. In addition, the experimental results were adjusted to nine mostly used models, to estimate the drying conditions required to achieve a desired final moisture content. Modified Page and Page were the models with better fit to experimental results. Furthermore, a computational simulation of temperature evolution and distribution inside the dryer is presented. These results agree with those obtained experimentally.

Keywords: medicinal plants, indirect solar drying, mathematical model, colorimetric study, computational analysis

1. Introduction

The knowledge of medicinal plants extends to any part of the world where man has traditionally needed them to cure his illnesses. Thus, a mixture of magic and religion, combined with necessity and chance, trial and error, the passage of different cultures has created a whole knowledge of plant remedies that has been the basis of modern medicine [1]. However, many studies have been performed to test if they are truly effective and, as a result of these studies, the therapeutic use of many medicinal plants as substitutes for pharmaceutical medicines has been applied successfully to cure or relieve diseases [2].

According to the WHO, herbal medicines include herbs, herbal material, preparations, and herbal products, which contain as active ingredients parts of plants or other plant materials, and their use is well established and widely recognized as safe and effective [3].

It has been shown in studies and reviews that medicinal plants have various properties that cure, for example, anticancer and antiviral activities [4],

antidiabetic properties [5], anti-dengue activities [6], infertility problems [7], contusion and swelling, plants that improves learning and retrieval processes, and facilitates memory retention, to treat Alzheimer disease, hepatitis, significant anesthetic activity, antiarrhythmic action and even anti-obesity [8–11].

In this work, three medicinal plants were selected, which for many years have been considered important because of the amount of medicinal properties they possess and because the literature has corroborated their effectiveness in various treatments.

One of the most used plants for medical purposes in the world is *Annona* (*Annona muricata* L.) which is a comestible tropical fruit widely cultivated through the world [12]. The roots of these species are used for their antiparasitic and pesticidal properties. Intensive chemical investigations of the leaves and seeds of this plant have resulted in the isolation of a great number of bioactive compounds which were found to display interesting biological including antitumor, anticancer, antiparasitic and pesticidal properties [13, 14]. Literature revealed that *Annona* fruit extracts possess antioxidant properties and were able to inhibit enzymes relevant to type-2 diabetes and hypertension [15].

On the other hand, also, *Moringa oleifera*, native to India, is fully utilized for its high nutritive values. The leaves have many minerals and vitamins and are utilized to treat malnutrition, to increase breast milk production in women, and as a powerful antioxidant, anticancer, anti-inflammatory, antidiabetic, and antimicrobial agent. There is literature that provides relaxing inducing properties [16–19].

Finally, Cymbopogon. It is native to Asia and grows in tropical and subtropical regions [19]. There are many medicinal uses of *Cymbopogon* because it has many functional properties. The leaves and the essential oil are consumed to help with dyspeptic disorders, colds, nervous conditions, and exhaustion. It was found that they have a potential anticarcinogenic action [20] and antimicrobial, sedative, spasmolytic, and carminative effects. It has also been shown to have antifungal, anti-inflammatory, antimutagenic, antimalarial, antinociceptive, antibacterial, and cholesterol reduction effects [21–26].

The preparation of medicinal plants depending on its use, is very important to reach the maximum potential action in the human body, but the most frequently performed preparation is drying the leaves and using them in teas or distilling them to produce essential oils.

Drying is fundamentally defined the elimination of the majority of plant moisture content, permitting the prevention of enzymatic and microbial activity and therefore preserving the product for extended shelf life. Moreover, the properties of medicinal plants are determined by their moisture content. Mostly of its preparation needs the elimination of water. Consequently, adequate dryers are very important, including control of temperature, velocity, and humidity values, and in many cases, direct solar radiation is forbidden to provide a rapid reduction in the moisture content without affecting the quality of medicinal plants. Drying process aids the marketing of plants, because drying allows to improve the distribution of the plants since it reduces both the weight and the volume, reducing the transport and storage needs [27].

Therefore, in this work, an indirect solar dehydrator was designed, with which the plant is protected from its high sensitivity to high temperatures and solar radiation.

2. Experimental study

2.1 Construction of the solar dryer

In this study, an indirect solar dryer type tunnel with solar technology hybridization was constructed (**Figure 1**): This dryer is hermetically sealed and is composed of three front sections. Each section contains two trays with a metallic
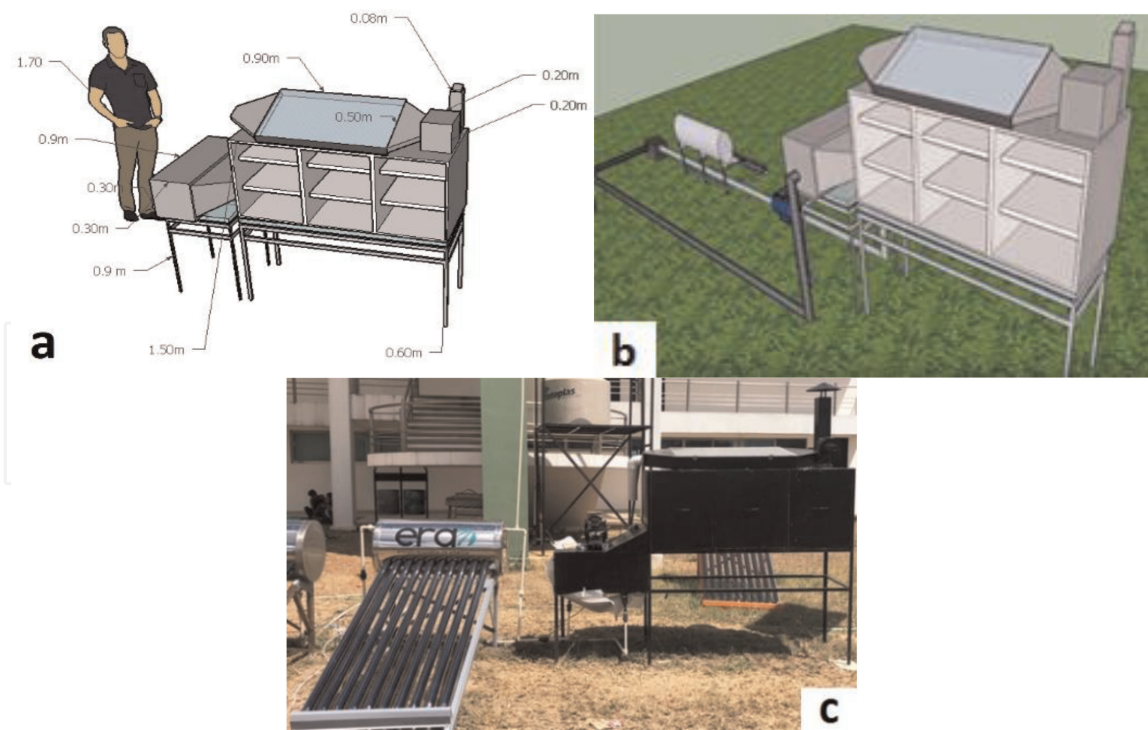
Figure 1.
Tunnel-type solar dryer: (a) main measurements and location of trays, (b) location of solar heater and solar air collector, (c) the indirect solar dryer in operation. Source: Own elaboration

mesh to support the hot air flow evenly. Each tray has a separation of 20 cm, as shown in **Figure 1a**. The drying chamber is connected to a solar water heater by a hopper, which drives preheated air inside, supported by a heat exchanger. Additionally, the dryer has a solar air collector installed at the top. This collector contains a fan that extracts the ambient air through the interior and directs it, with an increase in temperature, to the interior of the drying chamber (**Figure 1b**). The solar dryer has a 1/2 hp. motor that extracts ambient air into the solar air collector and an electric pump that recirculates the water in the solar heater, both systems work with a 280 W solar panel. **Figure 1c** shows the indirect solar dryer in operation.

2.2 Measuring instruments

In order to ensure the reliability of the experimental results, different measuring equipment were used at the different stages of the experimentation; Boeco mark food moisture measurement scale, model BMA150, with an accuracy of ± 1 mg (0.001%) was used to determine the initial and final humidity of the leaves. The leaf sample of approximately 1.5 g was cut and placed in the analyzer. Water activity in the leaves under study was measured by a mark team Rotronic HygroPalm, with an accuracy of $\pm 0.01\%$ mg. The mean of three measurements was reported at a room temperature of $24.5 \pm 1°C$. The temperature and humidity inside the drying chambers were measured using a Brannan thermo-hygrometer with temperature and relative humidity accuracy of $\pm 1°C$ and $\pm 3\%$, respectively. The weight of the samples was measured using a Boeco weighing scale, model BPS40plus, which have an accuracy of ± 0.001 g.

The weather parameters were monitored by the weather station located in the Faculty of Engineering of the Autonomous University of Campeche, which consists of a LI-COR Pyranometer, with which the global solar irradiance was measured; the accuracy is Azimuth: $< \pm 1\%$ on 360° to 45° of elevation. The relative humidity, ambient temperature, and wind velocity and direction were measured by NG Systems mark equipment, model RH-5X (accuracy $\pm 3\%$), 110S (accuracy

±1.1°C), Series #200P (accuracy ±3°), and P2546C-OPR (accuracy ±0.3 m/s), respectively.

2.3 Drying process and experimental setup

In this study, the kinetics of drying medicinal plants using an indirect solar dryer were analyzed experimentally to determine optimal operating conditions, evaluating the possibility of the integration of solar technologies in solar food drying. Samples of fresh leaves were cut from plantings on agricultural land, in the month of March 2019, in the city of Campeche, Campeche, Mexico. The experimental study was carried out from March 4 to April 26. The branches were cut, and the leaves were separated and selected to obtain a homogeneous group, based on maturity, color, freshness, and size. They were washed and weighed, and the width, length, and thickness were measured.

To analyze the initial and final humidity in the plants, the leaf sample of approximately 1.5 g was cut and placed in the analyzer. Water activity (a_w) is a parameter that determines the stability of the food with respect to the ambient humidity. It was measured for both fresh and dried leaves before and after the drying process using portable water activity meter.

The plants that were selected for experimentation were *Moringa oleifera*, *Annona muricata L.*, and *Cymbopogon citratus. Moringa oleifera*, is a plant that has generated great interest in recent years because of its attributed medicinal properties [28], contains more than 90 nutrients, different antioxidants, and all the 8 essential amino acids [29]. The main medicinal property of *Cymbopogon Citratus* is to be anti-inflammatory and antioxidant due to polyphenols, it contains, so it is used in cases of cancer and to combat arthritis among other properties [30].

Fresh and dried leaves were placed on a flat surface, and the colorimeter was placed on the leaves to measure color values. For each sample, the measurements were replicated four times, obtaining in each measurement the values L * (luminance), a * (brownness), and b * (darkness) [31].

The total color change (ΔE) was the parameter considered for the overall color difference evaluation, between a dried sample and the fresh leaf [32]:

$$\Delta E = \sqrt{(L_o - L)^2 + (a_o - a)^2 + (b_o - b)^2} \tag{1}$$

2.4 Mathematical modeling

In order to observe the drying behavior of medicinal plants, the moisture ratio against the drying time was plotted. The dry-based moisture ratio during the drying process was calculated using the following equation [33]:

$$MR_{db} = \frac{M_t}{M_0} \tag{2}$$

where M_t and M_0 are the moisture content in time t and the initial moisture content (kg water/kg dry matter), respectively.

2.4.1 Adjusting experimental drying curves

The experimental moisture-versus-time ratio was adjusted by nonlinear regression to nine thin-layer drying models (**Table 1**) for each drying kinetic of the

Model name	Model equation	Reference
Newton	$MR = \exp(-kt)$	[35]
Page	$MR = \exp(-kt^n)$	[36]
Modified page	$MR = \exp(-(kt)^n)$	[37]
Henderson and Pabis	$MR = a\exp(-kt)$	[38]
Logarithmic	$MR = a\exp(-kt) + c$	[39]
Two-term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	[40]
Two-term exponential	$MR = a\exp(-kt) + (1-a)$	[41]
Wang and Singh	$MR = 1 + at + bt^2$	[42]
Weibull	$MR = \exp\lfloor -(t/b)^\alpha \rfloor$	[43]

Source: Own elaboration.

Table 1.
Mathematical models used to predict the drying kinetics of medicinal plants.

medicinal plants. The criteria used to select the model that best fit the data experimental were the coefficient of determination (R^2) and the root of the mean square error (RMSE), considering that values of R^2 superior to 0.95 RMSE values below 0.06 indicate good fit [34]. In addition, a lower value of X^2 is considered as indicative of better fit. The adjustment was solved for the calculation of the different parameters involved in the selected fit models using the DataFix software version 9.1.

3. Results and discussion

Moisture tests were performed on fresh and dehydrated leaves; in all cases, the average initial humidity was 73.8%, the maximum readings were 79.58%, and the minimum readings were 68.2%. These readings agree with those reported in the literature (Banchero, Carballo, & Telesca, 2007). The initial average a_w was 0.976, the minimum measured was 0.96, while the maximum was 0.98. The average final a_w in all cases was 0.44, the minimum measured reading was 0.33, and the maximum was 0.58. The final a_w values indicate that there is no possibility of microbial growth in the dehydrated product obtained [44].

3.1 Weather conditions

Figure 2 shows the change in the weather parameters during the test period with three sunny days. As can be seen, a maximum solar global irradiance of 952 W/m^2 was achieved, with the average maximum values ranging between 874 and 962 W/m^2. The average ambient temperature varied of 30°C y 35.7°C. On the other hand, the minimum RH (relative humidity) ranged between 44 and 46%; the maximum average on the test days ranged between 60 and 81%.

Figure 3 shows the temperatures inside the drying chamber, solar radiation, and the ambient temperature during the hours with the highest solar incidence on the selected day as an example. The drying chamber consists of three sections with similar temperatures. The highest temperature reaches 50.7°C.
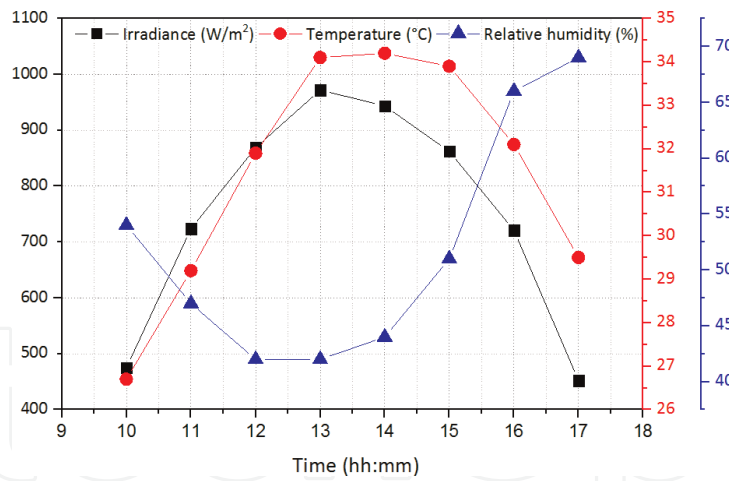
Figure 2.
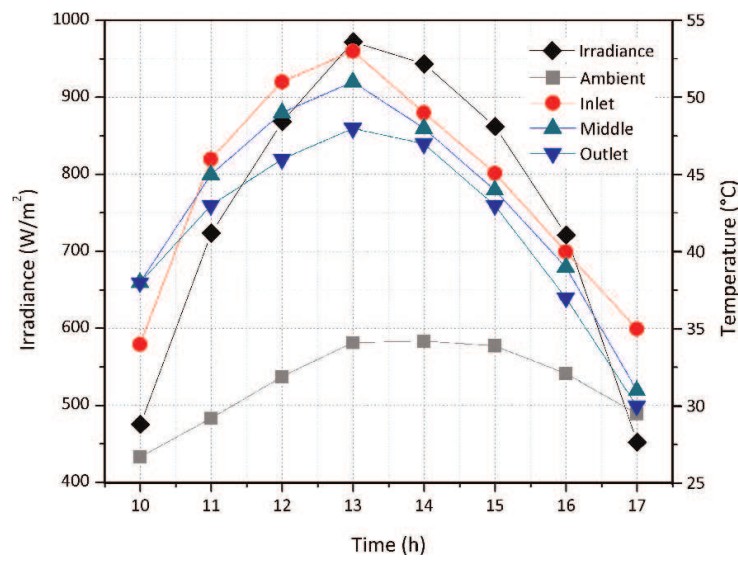*Average solar irradiance, ambient temperature, and relative humidity. Source: Own elaboration*

Figure 3.
Solar irradiance variation and temperature inside the drying chamber of the tunnel solar dryer. Source: Own elaboration
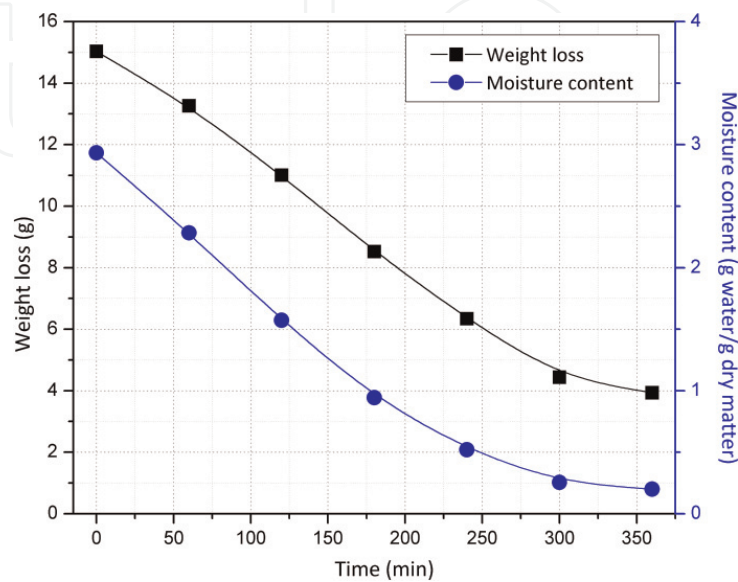

Figure 4.
Weight loss and moisture content depending on the drying time for Moringa oleifera *leaves. Source: Own elaboration*
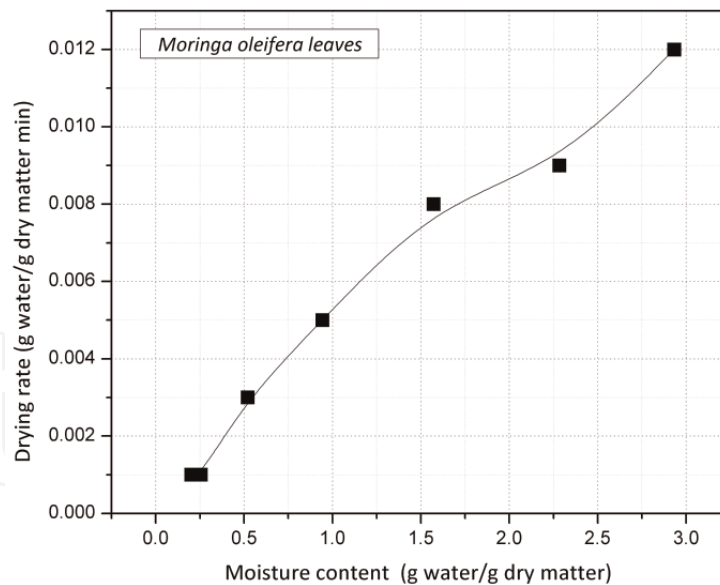
Figure 5.
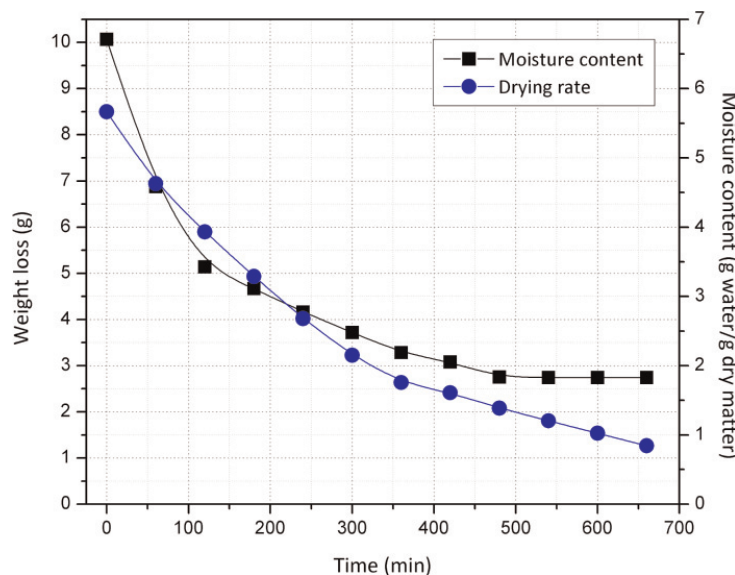*Drying rate as function of moisture content for a* Moringa oleifera *leaves. Source: Own elaboration*

Figure 6.
Weight loss and moisture content depending on the drying time for Annona muricata *leaves. Source: Own elaboration*

3.2 Solar drying kinetics

3.2.1 Moringa oleifera *leaves*

The weight loss stabilized upon reaching this sample 3.9 g; the final drying time was 360 min. It can be seen in **Figure 4** that the moisture content started at 2.93 g water/g dry matter, ending between 0.201 and 0.256. **Figure 5** shows the moisture content as a function of the drying rate; in this case no constant rate period was observed. The highest drying rate was found with 0.012 g water/g dry matter minute.

3.2.2 Annona muricata *leaves*

In the case of *Annona muricata* leaves, the total drying time was 500 min, (**Figure 6**); the initial moisture content was 5.667 g water/g dry matter, reaching a
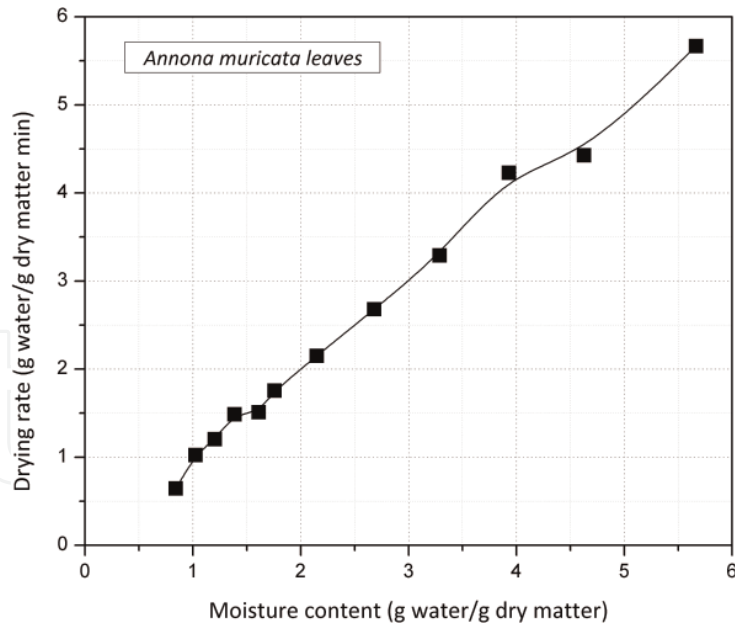
Figure 7.
Drying rate as function of moisture content for an Annona muricata *leaves. Source: Own elaboration*
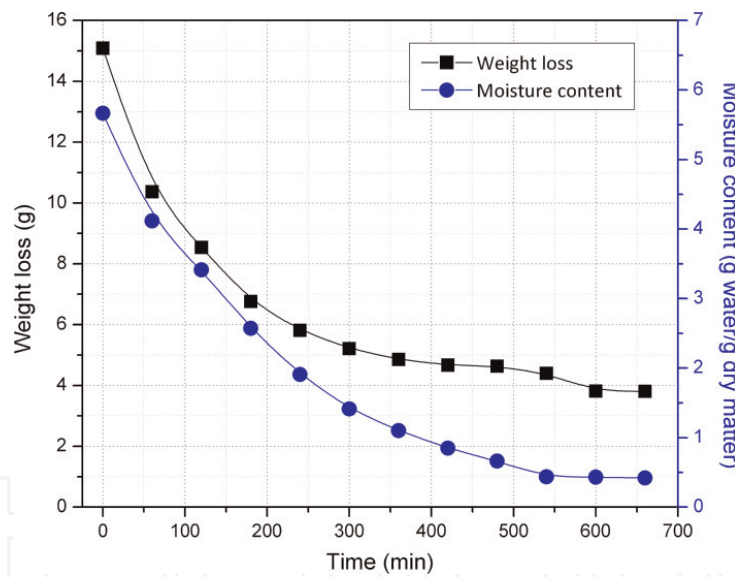

Figure 8.
Weight loss and moisture content depending on the drying time for Cymbopogon *leaves. Source: Own elaboration*

final moisture content between 0.843 g water/g dry matter and 1.204 g water/g dry matter. Reaching a final drying rate between 0.643 g water/g matter dry minute and 1.024 g water/g matter dry minute, the final weight of the sample was 2.7 g (see **Figure 7**).

3.2.3 Cymbopogon

As can be seen in **Figure 8**, the drying kinetics of the *Cymbopogon* sample stabilized in 660 min. The initial moisture content was 5.66 g water/g dry matter. The final moisture content was between 0.421 and 0.435. **Figure 9** shows that the highest drying rate was 0.026 g water/g dry matter min.
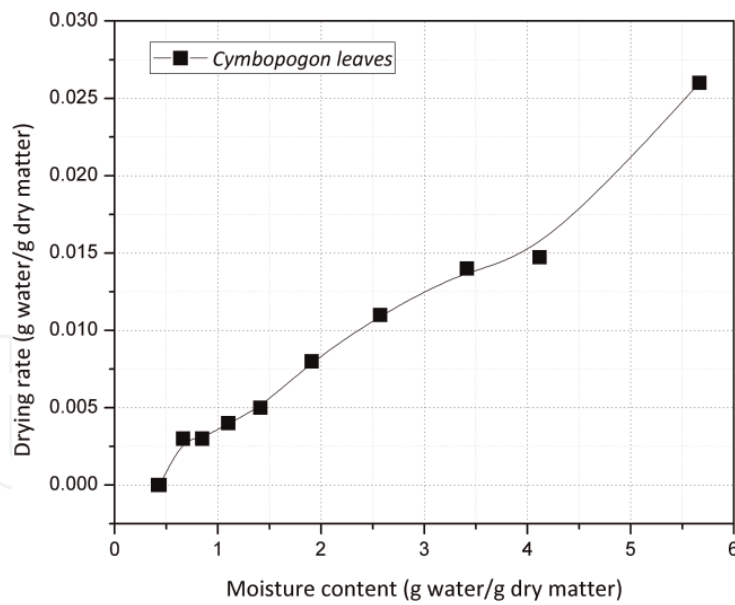
Figure 9.
Drying rate as function of moisture content for a Cymbopogon *leaves. Source: Own elaboration*
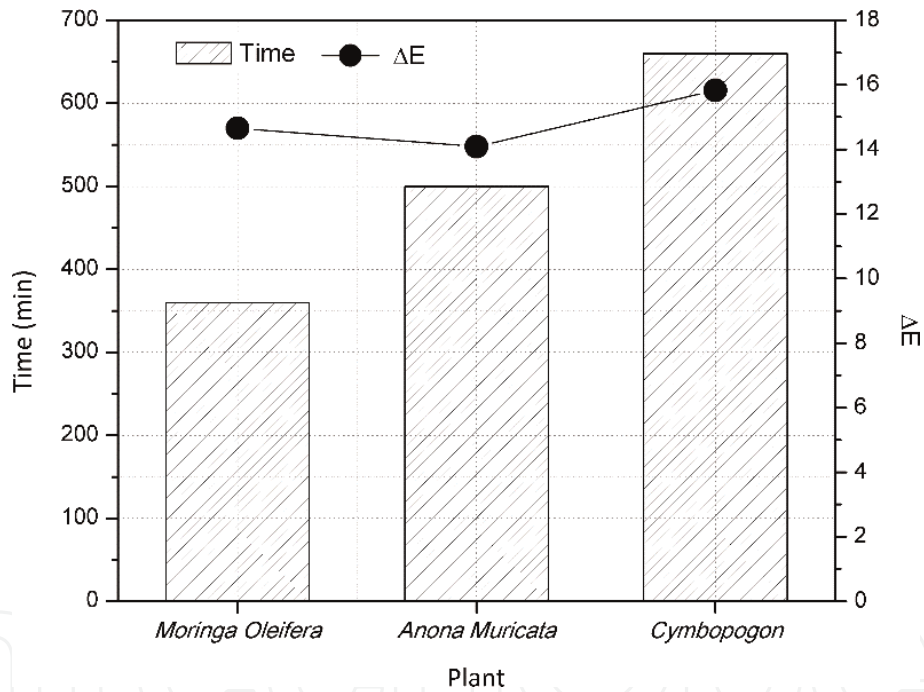

Figure 10.
Relationship between final drying time and ΔE in dehydrated leaves. Source: Own elaboration

3.3 Colorimetric analysis

Color is a primary characteristic perceived by the consumer of a product and plays an important role in food. The color of food is often an indication of the nutrients it contains. In addition, the color of a processed product is expected to be as similar as possible to fresh ones [45].

Table 2 shows the values obtained from L*, a*, and b*, in the medicinal plants studied in fresh and dry.

An insignificant variation in the parameters L*, a*, and b* obtained in the plants studied before and after the drying process can be seen in **Table 2**. This can be corroborated in **Figure 12**, in which ΔE is analyzed. The main reason for this color preservation is the protection against solar irradiation of the solar tunnel dryer, so

dehydrated plants are kept more similar to fresh ones. For this reason, it is preferable to dry in a closed and controlled environment, which is consistent with studies of Helvaci et al. [46].

It is important to note that in all cases the values of L*, a*, and b* decreased; this means that as the temperature increased (the three sections of the drying chamber reached up to 50.7°C). There was a tendency toward gray colors, a decrease in red colors (more brown), and an increase in yellow colors; these results agree with data reported by Bhardwaj et al. [47].

3.4 Computational analysis

Computational simulation is performed by using of a free software called Energy2D [48]. Simulation consists of temperature dependence upon time at dif-
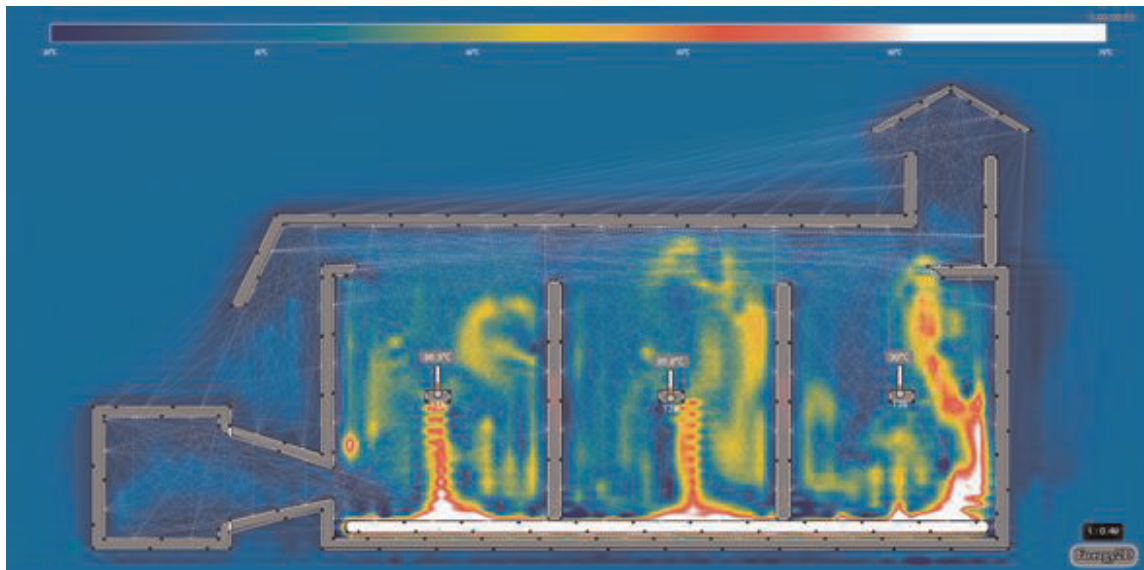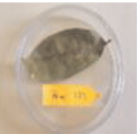

Figure 11.
Thermal behavior simulation of the dehydrator. Source: Own elaboration

L*, a*, b* values and drying	Medicinal plants		
	Moringa oleifera	*Cymbopogon*	*Annona muricata*
Fresh leaves L*, a*, b* values	L: 50.28 a: −6.76 b: 35.75	L: 50.2 a: −7.87 b: 21.81	L: 45.53 a: −8.41 b: 27.58
Dehydration with tunnel dryer L*, a*, b* values	L: 40.4 a: −2.61 b: 25.75	L: 41.27 a: 1.85 b: 13.14	L: 37.02 a: −5.24 b: 16.81

Source: Own elaboration.

Table 2.
Values obtained from L, a*, b* (fresh and dried) in the medicinal plants studied.*
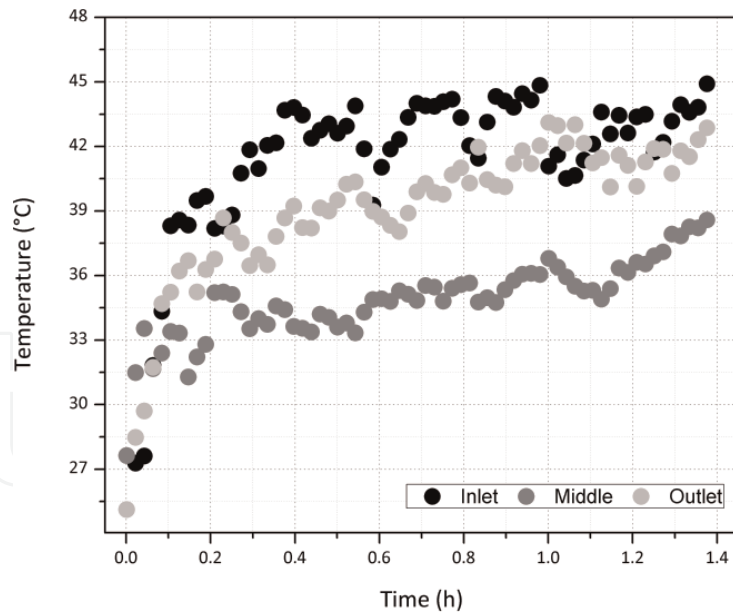
Figure 12.
Graph of thermal behavior simulation of the dehydrator. Source: Own elaboration

Annona		
Model	**Coefficients and fit parameter**	**Value**
Modified page	k	0.0116
	n	0.5685
	R^2	0.9941
	RMSE	0.0199
	X^2	0.0005
Cymbopogon		
Model	Coefficients and fit parameter	Value
Modified page	k	0.0369
	n	0.7545
	R^2	0.9988
	RMSE	0.0092
	X^2	0.0001
Moringa		
Model	Coefficients and fit parameter	Value
Page	k	0.0067
	n	1.5616
	R^2	0.9987
	RMSE	0.0119
	X^2	0.0001
Source: Own elaboration.		

Table 3.
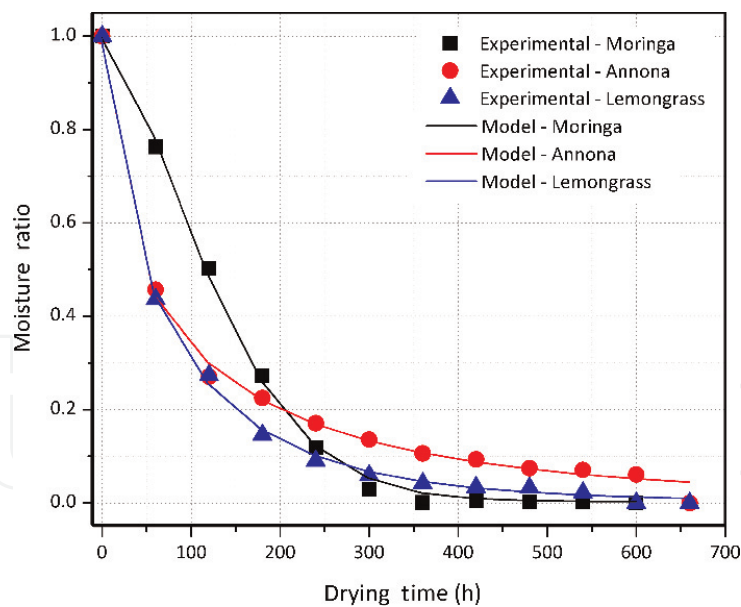*Results of regression analysis of the best adjusted models.*

Figure 13.
Experimental versus mathematical model. Source: Own elaboration

ferent zones. For the temperature evolution across time, thermal conduction and convection simulation mode was selected. For accurate results, also the thermal and optical properties of each material were chosen. The complete procedure of simulation can be found in Ref. [49]. In **Figure 11**, the thermal behavior of the dehydrator is shown and can be distinguished into three zones: left, middle, and right. Maximum reached values of temperature sensors, at the left, middle, and right zones were 45.2, 38.8, and 44.7°C, respectively, while its averages were about 41.4, 34.9, and 39.2°C, correspondingly. The temporal fluctuation of temperature is depicted in **Figure 12**.

The temperatures reached in the dryer with the hybridization of solar technologies remained stable during most of the day, with a variation between 45 and 50°C (**Figures 3** and **12**), which, as reported in the literature reviewed, are optimal to prevent the loss of important properties in vegetables and medicinal plants [46, 50].

3.5 Mathematical modeling

3.5.1 Adjusting experimental drying curves

The drying kinetics obtained experimentally in the medicinal plants were adjusted using the nine drying models mentioned in **Table 1**. **Table 3** presents the model that best fit for each drying condition. These models had the highest R^2 values as shown in **Table 2**.

Estimates of the statistical parameter for all experimental conditions showed that R^2 values ranged from 0.991 to 0.9988, indicating a good fit [34]. Therefore, these models adequately predict the selected plant drying kinetics. From the data, Modified Page model was the most suitable for describing drying processes of *Annona* and *Cymbopogon* drying conditions and Page for *Moringa* (see **Figure 13**).

4. Conclusion

Moringa oleifera, *Cymbopogon*, and *Annona muricata* have antioxidant, anticancer, anti-inflammatory, antidiabetic, antimicrobial, and many more positive effects

in the human body. The drying kinetics of this plants were analyzed using a constructed indirect solar dryer type tunnel. It was possible to obtain optimum temperatures for drying (45–50°C), and drying times were significantly reduced by keeping these temperatures constant for a longer time throughout the day.

The quality of the plants at the end of drying was confirmed when obtaining average a_w values of 4.4. The average final moisture content of the three medicinal plants varied between 0.8 and 1.5 g water/g dry matter. The moisture ratio was fitted to nine thin-layer drying mathematical models to select a suitable drying curve. The Modified Page and Page models showed the best fit to the experimental results. The time required to reach the equilibrium moisture content in all experiments varied between 250 and 350 min. The superior efficiency of the dryer allows a reduction of the important drying costs. This technology would allow agricultural producers to reduce costs while contributing to the improvement of the environment.

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