ANALYSIS OF THE THERMAL BEHAVIOR OF A TUNNEL-TYPE DRYER WITH HYBRIDIZATION OF SOLAR TECHNOLOGIES

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El hombre ha utilizado la energía solar para secar productos perecederos durante muchos años, logrando preservar una gran variedad de alimentos de forma natural; deshidratado es un método que respeta mucho las propiedades y el contenido nutricional de los alimentos. El consumo de hierbas medicinales y aromáticas en México es tradicional y generalizado. En este trabajo se realizó un análisis del comportamiento térmico de un secador solar tipo túnel, que implica la hibridación de tecnologías solares, como el calentamiento de agua y el calentador solar de aire, evaluando la posibilidad de utilizar la bomba fotovoltaica como medio coadyuvante para La generación de vapor. Los resultados experimentales mostraron que el secador indirecto de túnel solar que funciona con tubos evacuados y calentador de aire solar al mismo tiempo, es la tecnología más eficiente, con tiempos de secado promedio de 300 min y humedad final de 9.6%. Se realizó un estudio de colorimetría, análisis de la actividad del agua y velocidad de secado para controlar el proceso de secado. Está comprobado que es posible utilizar la energía solar para deshidratar los alimentos como medio de conservación, obteniendo también importantes ahorros de energía y contribuyendo al cuidado del medio ambiente.

Keywords: Solar drying, Tunnel-type solar dryer, drying chamber, solar drying kinetics

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Introduction

It is estimated that 80% of the world's population uses traditional herbal remedies and at least 35,000 species of plants have potential for medicinal use (Ramírez Hernández et al., 2018). In Mexico, according to Ministry of Healthat least 90% of the population uses medicinal plants (Lugo & Lugo, 2009). Drying is the most common method of preserving medicinal plants, but due to the high investment and energy costs, drying represents an elevated expense in the production of medicinal plants (Singh & Singh, 2017). It is necessary to adopt technologies that effectively reduce post-harvest losses through the application of appropriate management, processing and conservation methods (Mewa, Okoth, Kunyanga, & Rugiri, 2019); Some post-harvest practices can limit the obtaining quality of the products, due the losses of their natural properties as colour, flavour and aroma, as well as their healing properties. This can be during drying of the product or any subsequent conditioning and storage (Banchero, Carballo, & Telesca, 2007). Solar drying provides high product quality with minimal environmental impacts. It is an effective, inexpensive and safe method for conservation of agricultural and food products (Kumar, Sansaniwal, & Khatak, 2016). There are different technologies for solar energy use. In contrast to energy sources such as fossil fuels, which depend on limited resources, solar energy is received naturally throughout the planet, and its use does not imply the destruction of the environment (Rodríguez et al., 2017).

There are two methods of solar drying (direct cabinet solar dryer and indirect cabinet solar dryer) that were tested under tropical conditions to dry aerial parts of sacha coriander (Eryngium foetidum L.) The indirect method was found more suitable for drying E. (Banout et al., 2010); Moreover, a comparative study of the solar tunnel and open sun drying of moringa oleifera leaves was carried out. It is found that the tunnel dryer requires less drying time and is economically viable (Vaghela, Bhautik, Sengar, & In, 2018). The thermal models for greenhouse dryers was also studied (Chauhan, Kumar, & Gupta, 2017). The study evaluates the previous work on the thermal modelling of greenhouse drying systems, greenhouse air temperature, relative humidity inside the greenhouse, drying velocity, drying kinetics and drying potential.
On the other hand, colorimetry is a non-destructive physical method widely used to determine the colour of a sample. The CIELab colour system is widely used for food colour determination. The three parameters measured in this investigation are: luminosity (L), redness (a) and yellowness (b). The value of L varies from 100 (for perfect white) to 0 (for black) (Doymaz & Pala, 2002), The difference in clarity is analysed by ΔL and the deviation of the red-green achromatic point is Δa, while that yellow-blue deviation is Δb and the total colour change is ΔE. In this work, three medicinal plants were selected to determine the best conditions of solar drying by different direct technologies in terms of the effect of final humidity (db), water activity (aw) and colorimetry study. The plants were selected due to their medicinal properties and abundance in the Campeche region.

The Mentha spicate is native to Europe, it is grown in different regions of the country, because it gathers good culinary and agronomic characteristics, among its benefits is that it fights germs that produce bad odours in the oral cavity, giving the person some freshness and menthol, minimizes bowel symptoms irritable, gastric inflammation, excess gas, is antioxidant, among other properties (Alonso & Desmarchelier, 2014). Annona muricate L, Is a plant native to Mesoamerica cultivated mainly in the tropics of America, Africa and the Pacific Islands extending from Mexico to Brazil; among the many benefits it offers are some that stand out for being of great help to combat highly specialized diseases such as its anti-cancer elements that fight different types of tumours, also among others, important properties are found to be anti-inflammatory, anti-diabetic, anti-ulcer, contain enzymatic antioxidants and not enzymatic act for protection against the effects of deterioration (Madridejos Mora, 2016); finally, Cymbopogon, Currently grown in countries of subtropical to warm climate, its main medicinal property 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 (Luardini, Asi, & Garner, 2019).

2. Experimental set up

In this study, the kinetics of drying medicinal plants using indirect solar drying technologies were analysed experimentally to determine optimal operating conditions, evaluating the possibility of solar drying integration.

2.1 Materials y methods

Raw material. Mature medicinal plants, grown in Campeche, Mexico, were selected. The branches were cut, and the leaves were separated and selected to obtain a homogeneous group, based on maturity, colour, freshness and size. They were washed and weighed, the width, length and thickness were measured. The plants that were selected for experimentation were: Mentha spicate, Annona muricate L. and Cymbopogon, in sustainable Mexican agriculture, seeking to contribute to the country's food security.

2.1.1 Solar drying technologies.

Solar dryer tunnel. The tunnel dryer is hermetically sealed, is composed of 3 front gates and contains 2 trays in each section which have a metallic mesh with the intention of supporting the flow of hot air evenly, each tray has a separation of 20 cm. The drying chamber is connected to a solar water heater by means of 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 consists of a fan that extracts the ambient air through its interior and directs it, with an increase in temperature, to the interior of the drying chamber. Figure 1 shows the technical specifications of this dryer.

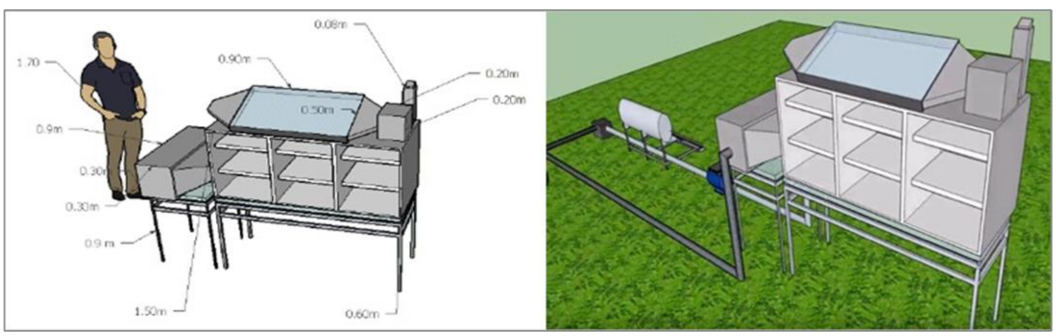

Fig. 1: Technical specifications of solar tunnel dryer

2.1.2 Instrumentation

Humidity.
A moisture analyser, Boeco BMA150, with an accuracy of ± 1 mg (0.001%) was used to determine the humidity of the leaves. The leaf sample of approximately 1.5 g and was cut and placed in the analyser. This procedure was performed for each condition before and after the drying process.

Water activity (aw).
Water activity 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, Rotronic HygroPalm, with an accuracy of ± 0.01% mg. The mean of three measurements was reported at a room temperature of 24.5 ± 1 °C.
Temperature. The temperature and humidity inside the drying chambers were measured using a thermo-hygrometer Brannan with temperature and relative humidity accuracy of ± 1 °C and ± 3%, respectively.

Weight.
The weight of the samples was measured using a Boeco balance, model BPS40plus, with an accuracy of ± 0.001 g.

Colorimetric analysis.
The colour measurement tests in fresh and dehydrated samples used a Huanyu digital colorimeter, model SC-10, repeatability ≤ 0.03 ΔE * ab.

Climatic parameters.
During the trial period, climatic parameters including temperature, humidity, air velocity and global solar irradiation were recorded by means of a meteorological station installed just in the experimental area. The specifications of the measuring instruments used in the experiments were considered from the data provided by the manufacturer (Table 1).

Tab. 1: Specifications and description of measuring instruments from the weather station

VARIABLE	*DESCRIPTION*	*MODEL*	*ACCURACY*
Global solar irradiance	LI-COR Pyranometer	LI-200R	Azimuth: < ± 1 % on 360° to 45° of elevation
Relative humidity	NRG Systems	RH-5X	± 3 %
Ambient temperature	NRG Systems	110S	± 1.1 °C
Wind velocity and direction	NRG Systems Wind sensor	Series #200P P2546C-OPR	± 3° ± 0.3 m/s

3. Results and Discussion

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 they varied of 30°C y 33.3°C, whereas the average maximum ambient temperature was 35.7°C. On the other hand, the minimum RH ranged between 44% and 46%, the maximum average on the test days ranged between 60% and 81%.

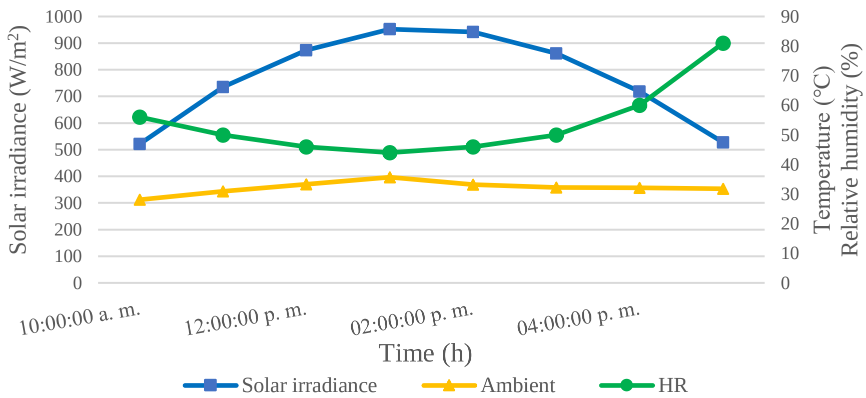

Fig. 2: Solar irradiance, ambient temperature, and relative humidity in one day during test period

3.2. Solar drying of medicinal plants

The dehydration of medicinal plants that are grown in the State of Campeche, Mexico through direct and indirect solar technologies is presented in order to evaluate the influence of air flow and temperature on the colour of the final product through the L* a* b* scale. The activity of water and humidity is analysed during the drying process.
Curves of drying kinetics, moisture content in dry basis and drying rate are presented in order to corroborate the process control.

The initial and final humidity and water activity values of the fresh and dried leaves are listed in Table 2 for each solar drying technology studied. The initial and final humidifies presented values within the ranges reported in the literature as normal. The final aw values indicate that there is no possibility of microbial growth in the dehydrated product obtained.

Table 2. Initial and final humidity and water activity obtained by different drying methods (average)

SOLAR DRYER TUNNEL				
Medicinal plant	***Initial humidity (%)***	***Final humidity (%)***	***Initial Aw***	***Final Aw***
Cymbopogon	73.632	8.27	0.99	0.46
Mentha spicate	79.581	11.11	0.96	0.4
Annona muricata L	68.177	10.03	0.98	0.42

3.2.1 Thermal characterization of solar dryer

The figures 3, 4 and 5, shows the effect of solar irradiation and ambient temperature of the drying chamber of the tunnel dryer, working with evacuated tubes, solar air heater and both systems at the same time, respectively. As mentioned above, the drying chamber consists of three sections, in the figures they are denoted as "entry, in middle and final", each of these sections.

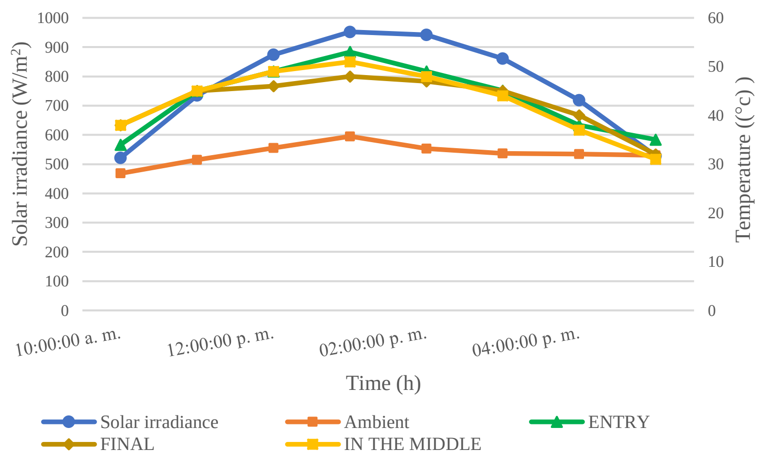

Fig. 3: Comparison of climatic parameters and temperatures reached in the indirect solar tunnel dryer working with evacuated tubes and solar air heater, one sunny day during test period

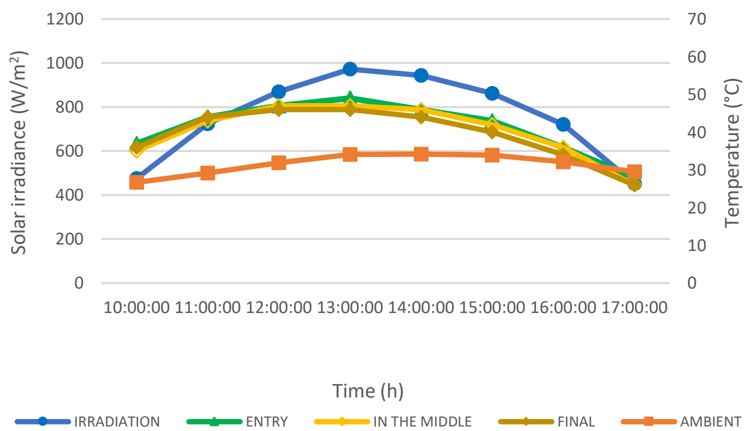

Fig. 4: Comparison of climatic parameters and temperatures reached in the indirect solar tunnel dryer working with solar air heater, one sunny day during test period.

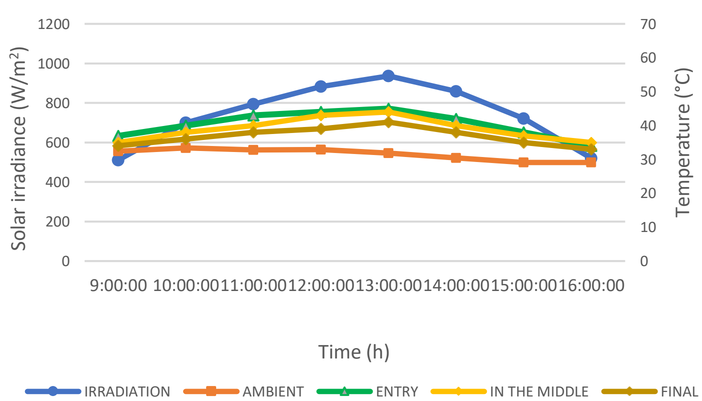

Fig. 5: Comparison of climatic parameters and temperatures reached in the indirect solar tunnel dryer working with evacuated tubes, one sunny day during test period

It can be seen in figure 3, the highest temperature in the dryer was achieved by working with both evacuated tubes and the solar air collector, the first section (the preheated air intake area from both the solar water heater and the air collector) reaches a higher temperature (51°C) that the two remaining sections, however, temperatures are very similar, the maximum temperatures in the 3 cases vary between 48°C and 51°C.

In the three cases analyzed, the temperature is very uniform throughout the drying chamber. The lowest temperatures were recorded by working the dryer with the solar heater of evacuated tubes (between 40°C and 42°C). Regarding the use of the solar air collector, the recorded temperatures ranged from 48°C to 46°C.

In figure 6, the temperature of the supply water of the evacuated tube heater (inlet) and its outlet temperature can be analyzed. As can be seen, the maximum temperature reached is 53°C at 1 pm, with a solar irradiation of 936.5 W/m^2. On the other hand, at the inlet temperature of the water throughout the test it is very similar to the ambient temperature at the beginning of the day, but it remains significantly higher, reaching up to 47°C this can be explained because the sun also heats the hose that conducts the water coming from the storage tank, which supports the system as it enters the evacuated tubes with an important temperature.

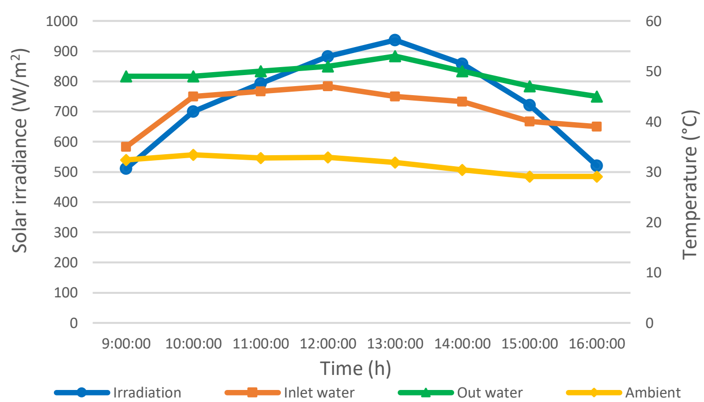

Figure 6. Inlet and outlet temperature of the supply water in the evacuated tube solar heater

3.2.2 Drying kinetics

In figures 7, shows the variation of the moisture content (db) as a function of the drying time, obtained in the three medicinal plants studied.

In this figure it can be analyzed that the fastest kinetics is carried out with *Mentha spicata*, which stabilizes in 300 min, this is logical due to the size of the leaf of this plant, which is very small and very thin. The drying kinetics of the *Annona muricata* in very similar to *Cimbopogon*, the first one is slightly faster at the beginning, although in the end both are practically finished in 420 min. This behavior was very consistent in all the experiments performed during the testing period.

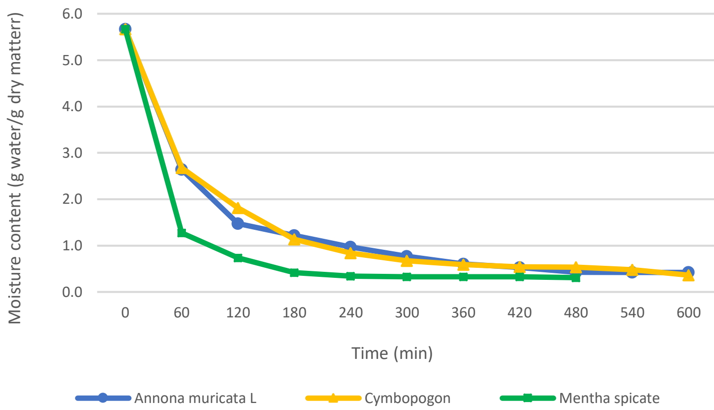

Fig. 7: Variation of moisture content with respect to the drying time in *the three medicinal plants studied.*

3.2.3. Colorimetric study

Table 3 shows the results of △E (represents the color difference in the samples), obtained in the study of colorimetry performed on medicinal plants (Mendoza, Dejmek, & Aguilera, 2006):

$$\Delta \boldsymbol{E} = [\![(\Delta \boldsymbol{L}^2) + (\Delta \boldsymbol{a}^2) + (\Delta \boldsymbol{b}^2)]\!]^{1/2} \qquad (1)$$

The results obtained indicate that the conservation of the green colour in the tunnel dryer was very remarkable (see table 3 y 4). The solar dryer conserved more the green colour in the Cymbopogon and in the Annona muricata L, degrading of important form the leaf of Mentha spicate.

Table 3. Colour variation ΔE as a function of drying time, considering the three modes of drying operation of the medicinal plants studied

Medicinal plant / **Dryer operation mode**	***Annona muricata L.***		***Cymbopogon***		***Mentha spicate***	
	△E	**Time**	**△E**	**Time**	**△E**	**Time**
Tunnel type	10	450	11	420	14	300

Table 4. Visual result of the colorimetry study carried out in dehydrated medicinal plants by different solar technologies

Medicinal plants / ***Drying method***	***Annona muricate L***	***Cymbopogon***	***Mentha spicate***
Tunnel type			

4. Conclusions

By introducing hot air into the indirect tunnel type dryer, with the evacuated tubes and the solar air collector, the maximum average temperatures reached were up to 55°C, which reduced drying times. In all the cases studied, a final moisture was obtained in the products according to the commercial standards, therefore, it is guaranteed that the proliferation of microorganisms that degrade the dehydrated product is avoided; in the same way, the temperatures with which a higher quality was achieved in terms of coloration of the dehydrated leaves were in the temperature range between 45°C and 55°C, these results are in agreement with (Müller & Heindl, 2006). For Mexican producers, these results are very important since is demonstrated the feasibility of use solar energy and the drying technologies evaluated, to dehydrate agricultural products. The use of this technologies is possible to reduce energy costs and at the same time, contribute to environmental care.

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