Analysis of the drying kinetics of sargassum using direct solar dryer and solar energy direct

Análise da cinética de secagem de sargaço utilizando secador solar direto e energia solar direta

Análisis de la cinética de secado del sargazo utilizando un secador solar directo y la energía solar directa

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ABSTRACT
This paper presents the analysis of the kinetics of sargassum drying using a direct solar dryer and the direct energy from the sun. Four mathematical models were applied: Newton, Page, Henderson and Pabis; and Midilli et al. The seaweed was brought from the coast of Cancun, Q. R, Mexico. With the direct solar dryer, a total of 6 hours were required to dry it, the final humidity ratio was 0.013. In the case of solar energy without dryer, i. e., in open air, 12 hours were required in two non-consecutive periods, and the final humidity ratio was 0.025. The solar radiation values, temperatures and mass variation were obtained as a function of time. The kinetic model that best simulated the drying process was that of Anderson and Pabis, obtained after the statistical analysis was performed, the activation energy was also obtained.

Keywords: sargassum drying, numeric model, direct solar dryer, direct solar energy, anderson and pabis model.
RESUMO
Este trabalho apresenta a análise da cinética de secagem do sargaço utilizando secador solar direto e a energia direta do sol. Foram aplicados quatro modelos matemáticos: Newton, Page, Henderson e Pabis; e Midilli et al. As algas marinhas foram trazidas da costa de Cancún, Q. R, México. Com o secador solar direto, foram necessárias 6 horas para secá-lo, a relação de umidade final foi de 0.013. No caso da energia solar sem secador, ou seja, ao ar livre, foram necessárias 12 horas em dois períodos não consecutivos, e a razão de umidade final foi de 0.025. Os valores de radiação solar, temperatura e variação de massa foram obtidos em função do tempo. O modelo cinético que melhor simulou o processo de secagem foi o de Anderson e Pabis, obtido após a realização da análise estatística, também foi obtida energia de ativação.

Palavras-chave: secagem de sargaço, modelo numérico, secador solar direto, energia solar direta, modelo de anderson e pabis.

RESUMEN
En este trabajo se presenta el análisis de la cinética del secado del sargazo utilizando un secador solar directo y la energía directa del sol. Se aplicaron cuatro modelos matemáticos: Newton, Page, Henderson y Pabis; y Midilli et al. Las algas fueron traídas de la costa de Cancún, Q. R., México. Con el secador solar directo, se requirieron un total de 6 horas para secarlo, la relación de humedad final fue de 0.013. En el caso de la energía solar sin secador, es decir, al aire libre, se requirieron 12 horas en dos períodos no consecutivos y la relación de humedad final fue de 0.025. Los valores de radiación solar, temperaturas y variación de masa se obtuvieron en función del tiempo. El modelo cinético que mejor simuló el proceso de secado fue el de Anderson y Pabis, obtenido después de realizar el análisis estadístico, también se obtuvo energía de activación.

Palabras clave: secado de sargazo, modelo numérico, secador solar directo, energía solar directa, modelo de anderson y pabis.

1 INTRODUCTION

In the last 15 years in the regions of the Caribbean, the Gulf of Mexico and Florida, among others, there has been an excessive arrival of seaweed called sargassum, which has affected both the environment and the economic activity of these regions. Annually, almost one million tons of sargassum reach the Gulf of Mexico from the Sargassum Sea in the Atlantic Ocean (SmetacekV and Zingone A, 2013). However, these seaweeds have various potential uses, as a source of amino acids, vitamins, proteins, and other polysaccharides; as soil amendments, for their nutrient content; transformed into biofuels; or as feed for livestock (Laffoley D d’A, et al., 2011).

There are more than 350 species of the genus Sargassum, most have a mature phase that grows anchored to the bottom of the sea by a structure like a root. Two species...
stand out for their abundance, S. natans and S. fluitans, both are holopelagic (Laffoley D d’A, et al., 2011). Seaweed has formed a global market of approximately $6 billion a year, of which 85% corresponds to food products and the remaining 15% to pharmaceutical goods (Xianglu Z, et al., 2021). It has been used as a textile dye adsorbent presents in effluents of the dying process, (Montenegro, et al., 2021)

Recently, research has been oriented to obtain biofuel from sargassum (López-Sosa LB, et al., 2020) and material for pavements (Salazar CBA, et al., 2021). Despite all the potential benefits of Sargassum, one of the main challenges for its use is its handling, since after collection, during storage, there are phenomena of decomposition, bad odors, and proliferation of harmful organisms.

An alternative to alleviate this problem focuses on the use of sargassum in applications after drying, a process that helps its conservation and management, as a source of thermal energy or as a composting support for the treatment of contaminated soils, among other uses. We considered primarily using an alternative source (clean energy) to carry out drying economically and efficiently.

In this paper we present the kinetics of sargassum drying, using a direct solar dryer and the direct energy from the sun, the quality of the dry product was analysed.

2 METODOLOGY

2.1 MATHEMATICAL MODELING

To describe the behavior of the model of the drying process of sargassum, the analysis using statistical methods of regression and correlation is required. Linear and non-linear regression models are important tools that allow us to find the relationship between the different variables, especially for those in which there is no previous established empirical relationship. In this work, the best model describing the process of drying sargassum with air was determined by using the Arrhenius multiple regression technique (López R, et al., 2009). ORIGIN software was used for this regression analysis. The humidity ratio is calculated as:

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

(1)

Where: \( M_t \) is the mass in time \( t \), and \( M_0 \) is the initial mass. The mathematical
models for a thin layer of material that were used in this research are listed in table 1. Those that best described the drying curve of sargassum have been selected (López R, et al., 2009, Kedinna Dias, et al., 2021). The following criteria were used to find the best model: the correlation coefficient ($R^2$) close to the unit, the lowest possible value of the chi-square ($\chi^2$), and the error of the mean square root ($RMSE$) that provides the standard deviation between the experimental and predicted values, is required to be as close to zero as possible. The expressions are:

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

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N-n}$$  \hspace{1cm} (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N}}$$  \hspace{1cm} (4)$$

where $MR_{exp,i}$ is the value of the humidity ratio measured experimentally, $MR_{pre,i}$ is the value of the predicted humidity ratio, for this measurement there are $n$ values, since it depends on the number of observations and the number of constants respectively (Yaldiz, O, et al., 2001).

Table 1. Models of drying kinetics.

<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page (Page G, 1949)</td>
<td>$MR = exp(-kt\times n)$</td>
</tr>
<tr>
<td>Newton (Jayas D, et al., 1991)</td>
<td>$MR = exp(-kt)$</td>
</tr>
<tr>
<td>Henderson and Pabis o Exponential (Henderson S and Pabis S, 1961)</td>
<td>$MR = a \times exp(-kt)$</td>
</tr>
<tr>
<td>Midilli et al. (Midilli et al., 2002)</td>
<td>$MR = a \times exp(-kt\times n) + bt$</td>
</tr>
</tbody>
</table>

Source: Own.

2.2 DIFFUSION COEFFICIENT

In the drying process, diffusivity is the only physical mechanism for the transfer of moisture to the surface. Fick’s second diffusion law, for a thin layer of product, defines it as:
\[
\frac{\partial M}{\partial t} = D_{\text{eff}} \frac{\partial M}{\partial x^2}
\] (5)

The initial conditions are:

a) the distribution of mass is considered uniform throughout the material;
b) the mass transfer is symmetrical with respect to the center;
c) the moisture content on the surface is in balance with the surrounding medium;
d) the diffusion coefficient is constant;
e) the shrinkage of the material is negligible.

Therefore, the boundary conditions are:

\[
t = 0, \quad -L < x > L, \quad M = M_0;
t > 0, \quad x = L, \quad M = M_e;
t > 0, \quad x = -L, \quad M = M_e
\]

The solution of equation (5), according to Akpinar E Bicer Y and Yildiz C, 2003 and Kaymak-Ertekin, F. 2002, is:

\[
MR = \frac{M_f}{M_o} = \frac{8}{\pi^2} \exp \left( -\frac{D_{\text{eff}} \pi^2}{4L^2} t \right)
\] (6)

The effective diffusivity of humidity is determined with the graph of the experimental data of the \( \ln(MR) \) vs time

\[
\ln(MR) = \ln \left( \frac{8}{\pi^2} \right) - \left( \frac{D_{\text{eff}} \pi^2}{4L^2} \right) t
\] (7)

The slope of the previous line is the value of the effective diffusivity at different temperatures:

\[
slope = -D_{\text{eff}} \left( \frac{\pi^2}{4L^2} \right)
\] (8)

Effective diffusivity varies with temperature according to Arrhenius dependence, as:
\[ D_{\text{eff}} = D_0 \exp \left( -\frac{E_a}{RT} \right) \quad (9) \]

in which \( D_0 \) is the diffusivity at infinite temperature, \( E_a \), is the activation energy for moisture diffusion, \( T \) is the temperature and \( R \) is the gas constant. In this case the equation is:

\[ \ln D_{\text{eff}} = \ln(D_0) + \left( \frac{E_a}{R} \right) \frac{1}{T} \quad (10) \]

3 PROTOTYPE

The prototype used operates in conditions of natural convection, consists of a box of 1.00 m in length and 0.60 m in width, which has in the background a perforated sheet and a black painted paint, through which the air enters. At 0.5 m from the bottom, it has a 20-gauge mesh, in which the product to be dried is placed, finally it is covered with a 0.005 m thick glass. The hot air outlet is an 0.10 m high and 0.30 m wide opening. An outline of this prototype is presented in Figure 1 (A).

In the case in which no solar dryer was used, the sargassum was placed on a table with plastic mesh of 0.50 by 0.50 m in area and the thickness of the product was no greater than 0.05 m, Figure 1 (B). This was done because it does not matter if the final product is contaminated with any element contained in the environment, since it is going to be burned, when applied as fuel.

The temperature of the air and the product to be dried in the air chamber was determined with three properly calibrated K-type thermocouples, which have an accuracy of ± 0.1 °C. The first thermocouple records the air temperature at the inlet of the chamber, the second is inside one of the samples to be dried and the third is at the exit of the same chamber. The relative humidity of the ambient air was measured with an EXTECH digital hygro-thermometer model EA25, with a measurement accuracy of ± 0.1%. It was located on the outside of the solar collector. The measurement of the mass of the product was determined with a SARTORIUS digital balance model BL1505, with a measurement accuracy of ± 0.01 g, located outside the drying chamber. For the measurement of solar radiation, an EPPLEY pyranometer model 8-48 was used, with a measurement accuracy of ± 1 W/m², located on the glass cover of the solar collector. All variables were recorded using the lab-View software duly programmed at 10-minute intervals. In the case of
drying without a dryer, only two thermocouples were used, one was placed on one of the branches of the sargassum and the other was used to measure the temperature of the environment. For the measurement of relative humidity, product mass and solar radiation, the same elements described above were used, including the recording of the same, both tests were simultaneously carried out.

Figure 1. (A) Direct solar dryer diagram and (B) Direct solar table. 1) structure or base; (2) support; (3) glass; (4) metal mesh; (5) product to be dried.

Source: Own.

4 EXPERIMENTAL PROCEDURE

The sargassum was collected in the sea before it arrived at the beach of Cancun, Q. R.; thoroughly washed and drained before its packing. Samples of 100 g (wet mass) were separated, frozen to -12 °C, and transferred to Mexico City, the same day. At the lab, they were kept in the freezer at -18 °C for preservation. For the drying process, each sample was thawed to 20 °C, mashed and drained. The 0.100 kg sample was placed in the intermediate tray and the drying process was started with the thermocouples in place. The Lab-View software recorded the temperatures of the environment, the air at the entrance and exit of the drying chamber and the product, in addition to the solar radiation; the record was taken every ten minutes. Eight experimental tests were conducted.

5 RESULTS AND DISCUSSION

The drying evaluation was carried out during the months of March and April 2023, the solar radiation that affected the solar heater is shown in Figure 3. The maximum value was 995.00 W/m² on average considering both months, and occurred around 14:00 hours
of the day, the equation obtained for this radiation as a function of time is:

\[ I = 3177.96 - 1334.12 \times 10^2 - 7.47 \times 10^3 + 0.0853 \times 10^4 \]  \hspace{1cm} (11)

and the amount of total energy received was 6.8 kW/m² h on average for both months. The maximum air temperatures in the drying chamber were 65.0 °C at the inlet, at the outlet of 59.2 °C and in the sargassum of 62.3 °C, they occurred when the solar radiation also had its maximum value, that is, at 14:00 hours. Values recorded are included in Figure 4.

Figure 3. Incident solar radiation on the collector.

![Figure 3](image1)

Source: Own.

Figure 4. Temperature distribution in the drying chamber.

![Figure 4](image2)

Source: Own.

The average mass at the beginning of the sargassum samples was 0.100 kg and after 6 hours in the drying chamber, the humidity ratio was 0.013 kg\(water/kg_{dm}\), which is about 16 % of the original. In the case of direct sun exposure, the humidity ratio was 0.019 kg\(water/kg_{dm}\). Figure 5 shows the curves of the humidity ratio during the experimentation of the sargassum samples, in this graph the average of the eight evaluations carried out is considered. These values apply to the numerical models.
mentioned above. Seeking to determine the one that best described the evolution of the drying process, the previously described conditions were applied: using as a criterion $R^2$ close to the unit and $\chi^2$ as close to zero. The kinetic model that best describes the drying process of sargassum, applying the experimental processes described, is that of Anderson and Pabis. Table 2 summarizes the values of the equations of the model obtained, as well as the values of $R^2$ and $\chi^2$.

Figure 6 shows the curve of the numerical model obtained with the values of $R^2$ and $\chi^2$ for the solar dryer and Figure 7 displays it for solar direct energy.

Figure 5. Moisture ratio of the sargassum drying process.

Figure 6. Graph of the numerical model of Henderson and Pabis for Solar dryer.
The activation energy of water was determined with the method of the Arrhenius equation, described with equation (10), therefore, it was necessary to make the graph of the ln (RM) against time and the slope of this corresponded to its value. Figure 7 shows the corresponding graph, from which a value of \( E_a = 36.4 \, \text{kJ/mol} \) for the activation energy is obtained.

**6 CONCLUSIONS**

The problem of sargassum has increased lately causing serious damage to the economy of the populations of the Caribbean. Drying is an alternative process to the management of sargassum for its subsequent use; we determined the kinetics of an environmentally sustainable drying process, using and solar dryer and solar direct energy. Samples of approximately 0.10 kg were dehydrated up to 15% of the initial humidity in approximately 6 hours for solar dryer and 12 hours for solar direct energy. The evaluation was carried simultaneously for both cases. The numerical prediction model of the drying process that provided the best results was the Anderson and Pavis. The criteria used for its determination were the correlation coefficient \( R^2 \) close to the unit, the lowest possible value of the chi-square \( \chi^2 \). The equations of the models obtained are:

- \( \text{MR}= 96.04 \exp(0.00414t) \) for solar dryer,
- \( \text{MR}= 135.848\exp(0.00368t) \) for solar direct energy.
To determine the activation energy of the water, the method of the Arrhenius equation was used, obtaining $E_a = 36.4 \text{ kJ/mol}$. With these values it is possible to design a novel drying system, which uses clean energy and allows the use of sargassum, preserving its characteristics of interest for different applications without the inconveniences of health and decomposition that implies the handling and storage of this fresh or wet material.
REFERENCES


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