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Drying Kinetics of *Leucaena esculenta* Seeds Using a Solar Dryer

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Abstract: The drying kinetics and physical and chemical characteristics of *Leucaena esculenta* seed drying using a forced convection solar dryer are described. The drying kinetics behavior is examined for three experiments under climate conditions of three different winter days in central Mexico, observing significant effects related to the reported pH levels of the seeds with values of 6.34, 5.98, 5.97, 5.82, and 6.07. The airflow measurements inside the drying chamber were observed, including the geometric dimensions, color, appearance, weight, and moisture loss, and the effective diffusivity coefficient (D_{eff}) of *Leucaena esculenta* with values between 1.23×10^{-7} and 8.09×10^{-9} $\frac{m^2}{s}$. Solar drying, with the technology used in this study, is a viable alternative to give added value to *Leucaena esculenta*. This study can be the basis for developing alternatives to preserve seeds for animal and human consumption.

Keywords: drying kinetics; solar dryer; *Leucaena esculenta*; legume drying

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1. Introduction

The guaje, a tree species of the Leucaena genus of the legume family, is a globally distributed plant. It is found from the south of the United States of America to the north of South America, with two variants: the red guaje called *Leucaena esculenta* and the green guaje or white guaje called Leucaena leucocephala [1]. *Leucaena esculenta*, considered native to Mexico [2], has been consumed since pre-Hispanic times and is found in the central and southern states of the country [3], mainly Oaxaca, Chiapas, Guerrero, and Morelos. The case study described here has been developed in this last location. This species is characterized by producing a pod of length between 11 and 25 cm and width between 1 and 3 cm, which contains an approximate amount of 15 to 30 green seeds inside, which measure 1 cm long and between three and six millimeters wide [4].

Leucaena esculenta is used as animal and human food [5], as a source of firewood and shade in permanent plantations [6], and is considered part of the customs of pre-Hispanic cultures [7] and traditional herbal medicine [3]. It has been reported to provide quality forage for the livestock sector primarily during drought periods due to its tolerance to drought and is quickly consumed by cattle [2,8]. It has also been suggested that forage (leaves of *Leucaena Esculenta*) may be helpful as a food supplement for laying hens with low levels of supplementation [9]. *Leucaena esculenta* is considered an alternative food for human consumption due to the minerals, proteins, and crude fiber it contains [7], vitamin A, and fatty acids [3]. Furthermore, the Leucaena species is part of the cultural identity in its consumption in various parts of the country, being produced all year round (Leucaena leucocephala); on the other hand, *Leucaena esculenta* is mainly harvested between August and February. In the case of the State of Morelos, the *Leucaena esculenta* species is produced between December and February and is used during this season by the population. The seeds are traditionally consumed in different ways, such as toasted snacks with salt and lemon, raw sauces, and the most representative in the traditional cuisine of the state of Morelos, Huaxmole, a typical stew with great acceptance for its flavor [1].

Human consumption of *Leucaena esculenta* is limited by its short production season, even more so if one wishes to revalue its consumption by extending it to other regions or countries. Currently, cold storage chambers are used to delay the maturation of the seed, but they are an expensive alternative and need to be more accepted in the context of traditional use of the seed. Although there are different methods of food conservation, whether by inhibition, inactivation, or the avoidance of recontamination, currently, great efforts continue to be made to improve the quality of food products for consumer satisfaction [10]. However, some of these alternatives are not viable because they raise the cost of processed seeds and frequently require a high energy consumption derived from non-renewable sources.

For this reason, there is still interest in developing options to preserve *Leucaena esculenta* seeds and looking for economically attractive alternatives that use renewable energy to revalue human consumption. One of these alternatives is, for example, solar dryers that have been widely used in different investigations [11] and have demonstrated their viability [12]. Their primary function is to capture the radiation provided by the sun as an inexhaustible and clean source. They are manufactured with commercial and low-cost materials that reach adequate temperatures for drying food [13,14], reducing the humidity of the product to avoid the proliferation of microorganisms and, in turn, reducing its weight and extending its shelf life, obtaining promising results in the drying of meats [15–17], fruits [18–20], and vegetables [21–25]. This process is carried out using mathematical models that effectively describe the phenomenon of drying kinetics [26–28], where the effective diffusivity coefficient may be the most important because it depends on the drying conditions and the properties of the material to be dried to remove the moisture content.

Derived from the interest in cultivating *Leucaena esculenta* in Mexico and the absence of previous studies on the drying of the species for human consumption, this research focuses on obtaining seed drying kinetics for conservation, describing it through the Fick diffusion model. A forced-flow indirect solar dryer design is used under different climatic conditions, such as solar radiation, temperature, and airflow. On the other hand, since there are no studies on the drying kinetics of *Leucaena esculenta* seeds, the pH and effective diffusivities obtained were compared with some related results previously reported in the literature.

2. Materials and Methods

2.1. Leucaena esculenta

Several samples of *Leucaena esculenta* pods were collected from a tree in the municipality of Yecapixtla Morelos (18.853° N latitude and 98.869° W longitude) during the winter cycle at the beginning of 2023. The pods were collected using the collectors' experience: The pods were selected regardless of size. However, the pod's color was considered; it should have been homogeneous (reddish) over the entire surface, and the seeds should have the same size and a solid consistency to the touch to ensure their maturity (Figure 1).

Figure 1. *Leucaena esculenta* pod samples.

On the other hand, several experiments were carried out, but the results presented in this study are only a small sample of multiple repetitions performed since no significant statistical variations were observed beyond the ones described below. For this study case, five seeds are presented (Figure 2). In addition, a comparison was made between the dried seeds obtained in the drying process with this study and the seeds of pods that dried naturally on the tree to compare the final quality.

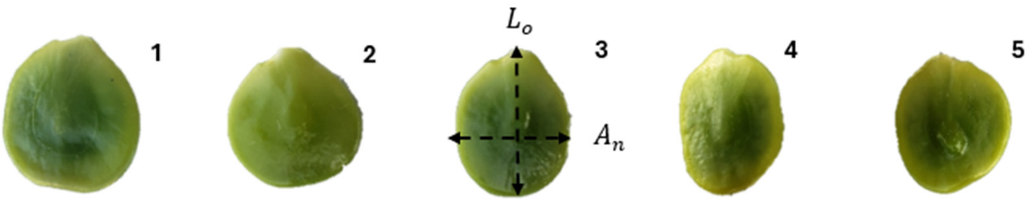

Figure 2. *Leucaena esculenta* seed. Superscripts indicate sample number.

The experiments described below were conducted at the exact location on 20 January, 2 February, and 7 February 2023.

The pH is experimentally calculated from the seed pulp at the beginning and end of the drying process using an ATC refractometer (MPN: 43217-71864). To measure the moisture content and weight loss, a thermobalance (model: XY-110MW) is used at the beginning of the process as a parameter to estimate the appropriate drying time of *Leucaena esculenta* at a temperature of 105 °C. A KUBEI jewelry scale is also used to calculate the weight of the sample during the drying process. The physical dimensions (minor axis "*An*" and major axis "*Lo*") are measured with a digital caliper (YUGENER) with an accuracy of ±0.02 mm. These dimensions are measured to describe the samples' contraction during and at the end of the drying process.

2.2. Experimental Model

The drying test of *Leucaena esculenta* (see Figure 2) was carried out on 20 January, 2 and 7 February 2023, outdoors at EESYecapixtla at the location described in Section 2.1. All experiments were conducted under environmental conditions that considered solar radiation, ambient temperature, the temperature inside the drying chamber, and the airflow rate entering the solar collector. For this, an indirect and forced-flow solar dryer was used with the following dimensions of the collector: length of (L_c) 2.145 m, width of (W_c) 0.95 m, and height of (D_c) of 0.13 m; and for the chamber: height of (L_{ch}) 1.27 m, width of (W_{ch}) 1.01 m, and depth of (D_{ch}) 0.455 m (see Figure 3). In the drying chamber, the samples are placed while airflow is passed through the solar collector ducts, increasing their temperature before being introduced to the chamber. The equipment was located facing south to take advantage of maximum solar radiation during the days of the experiment. The configuration and characteristics of the equipment, electronic control, data acquisition, and the meteorological station, which played a crucial role in measuring climate data, are described in [29].

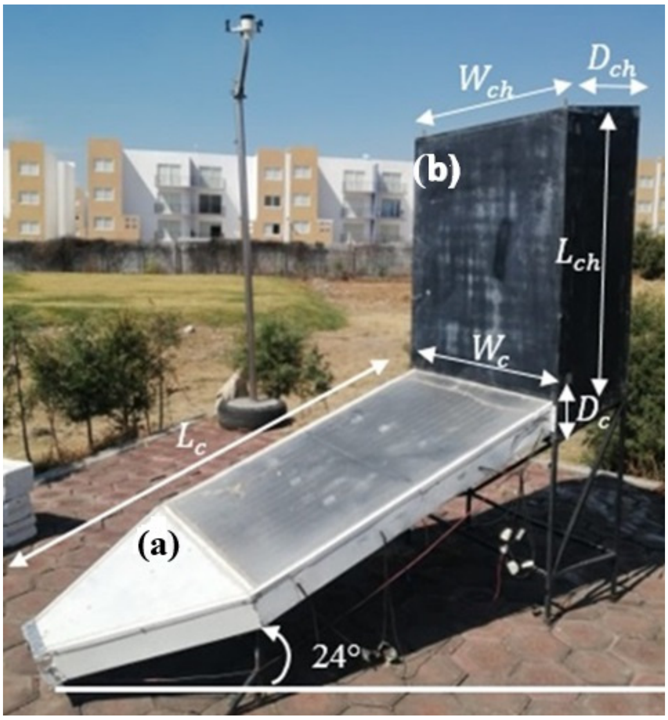

Figure 3. Solar dryer. (**a**) Solar collector and (**b**) drying chamber.

2.3. Drying Kinetics

The drying curves of *Leucaena esculenta* were determined experimentally using the Fick model. This model has been used effectively in other works, obtaining satisfactory results in the drying kinetics of some legumes [29–32]. For this reason, the one-dimensional Fick diffusive model is used, which describes the transport mechanism in regions of decreasing drying rate, as per Equation (1).

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial^2 x^2}, \tag{1}$$

where M is the moisture content (g water/g dry mass), T is the time (s), X is the length (m), and D_{eff} is the effective diffusion coefficient of moisture in solids $(\frac{m^2}{s})$.

The Fick diffusion equation was solved depending on the drying conditions and the product properties (*Leucaena esculenta* samples). For this, it was considered that the moisture distribution is uniform in the dough; the mass transfer is symmetrical to the center; there is an equilibrium between the moisture surface and the surrounding air; there is negligible mass transfer resistance at the surface compared to the internal resistance of the sample. The transfer is carried out by diffusion; the diffusion coefficient is constant, and the shrinkage is negligible. Also, they were considered in the form of sheets with thickness L, which dry on both sides, with boundary conditions at $= 0$, $x = 0$, $x = L$, and $M = M_0$. Therefore, the solution of the Fick diffusion equation is presented by Equation (2).

$$MR = \frac{8}{\pi^2}exp^{[-\frac{\pi^2 D_{eff}}{4L^2}t]}, \tag{2}$$

where *MR* is the moisture ratio (dimensionless term), and *L* is the half-slab thickness of the slices (m).

The effective diffusivity coefficient is calculated by applying the properties of logarithms to Equation (2). Thus, D_{eff} is calculated by plotting the drying time (*t*) against experimental values of the logarithmic moisture ratio ln (*MR*), giving a straight line with a slope (*S* slope), as per Equation (3).

$$S_{lope} = \frac{\pi^2 D_{eff}}{4L^2}. \quad (3)$$

3. Results

3.1. Weather Conditions

The *Leucaena esculenta* drying experiments, a crucial part of our research, were conducted over three days. On 20 January 2023, a day with partly cloudy skies, and on 2 and 7 February 2023, clear days, we meticulously measured and recorded solar radiation and ambient temperature using our weather station. As depicted in Figure 4, the solar radiation consistently exceeded 600 $\frac{W}{m^2}$ for all three days, and the temperature rose above 22 °C from 11:00 h onwards, providing valuable data for our study.

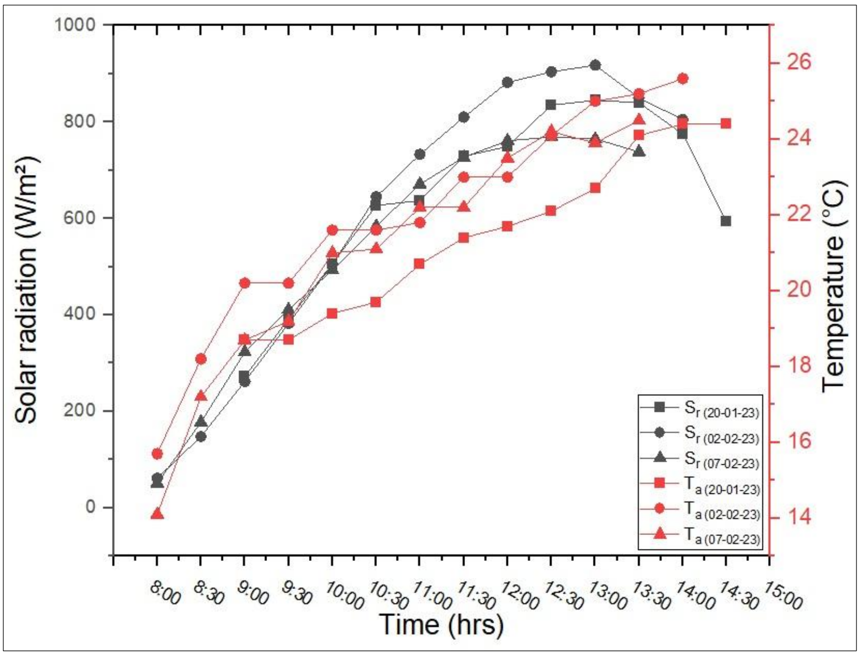

Figure 4. The behavior of solar radiation S_r and ambient temperature T_a for different days.

The data on airflow velocity and the temperature inside the drying chamber, as shown in Figure 5, reveal the dynamic nature of our experiments. The variations in airflow velocity, attributed to the gusts of wind in the experimental area, create a signal with some fluctuations, adding an element of unpredictability to our study; however, the drying time required is not significantly affected by these variations, as described below. The temperature inside the chamber, influenced by the solar collector's solar radiation (Figure 4), also presents some fluctuations related to the airflow speed, maintaining the dynamic nature of our experiments.

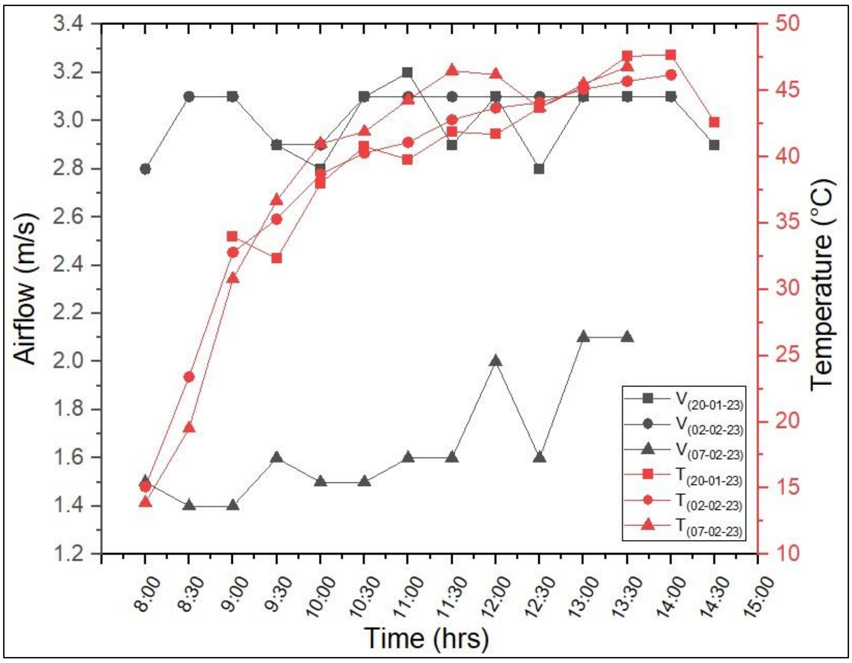

Figure 5. Airflow and temperature inside the drying chamber.

3.2. Characteristics of *Leucaena esculenta*

In this work, the results for only five seeds are described for clarity. There were no significant statistical variations in the analyses for larger samples. Thus, the geometric dimensions and pH of the *Leucaena esculenta* samples (1–5) used for drying (Figure 2) were taken before and during the study. The quantitative results can be seen in Figure 6, which shows the change in dimensions, thickness (Ti), minor axis (An), and major axis (Lo). In the case of sample 1, the initial dimensions for $Ti^1_{(20\text{-}01\text{-}23)}$, $An^1_{(20\text{-}01\text{-}23)}$, and $Lo^1_{(20\text{-}01\text{-}23)}$ are 2.8, 10.7, and 11.2 mm, respectively; thus, after 13:30 h, there are no changes. However, the initial dimensions for the remaining samples are as follows: sample 2, $Ti^2_{(02\text{-}02\text{-}23)} = 2.8$, $An^2_{(02\text{-}02\text{-}23)} = 7.4$, and $Lo^2_{(02\text{-}02\text{-}23)} = 9.2$ mm; sample 3, $Ti^3_{(02\text{-}02\text{-}23)} = 2.4$, $An^3_{(02\text{-}02\text{-}23)} = 6.3$, and $Lo^3_{(02\text{-}02\text{-}23)} = 9.2$ mm; sample 4, $Ti^4_{(07\text{-}02\text{-}23)} = 2.4$, $An^4_{(07\text{-}02\text{-}23)} = 7.9$, and $Lo^4_{(07\text{-}02\text{-}23)} = 11.1$ mm; and sample 5, $Ti^5_{(07\text{-}02\text{-}23)} = 2.1$, $An^5_{(07\text{-}02\text{-}23)} = 7.9$, and $Lo^5_{(07\text{-}02\text{-}23)} = 9.7$ mm. For samples (2–5), these do not change after 12:30 h. It should be noted that sample 1's drying process began at 9:00 h, one hour later than the rest of the samples, which explains this lag. However, the results show for all experiments that, after approximately 4 h, there are no longer changes in the dimensions of *Leucaena esculenta*. In the case of the pH of *Leucaena esculenta*, Table 1 shows that it rises slightly for all cases.

Table 1. pH before and after the drying process.

Sample	pH	
	Before	**After**
1	5.56	6.34
2	5.56	5.98
3	5.27	5.97
4	5.31	5.82
5	5.26	6.07

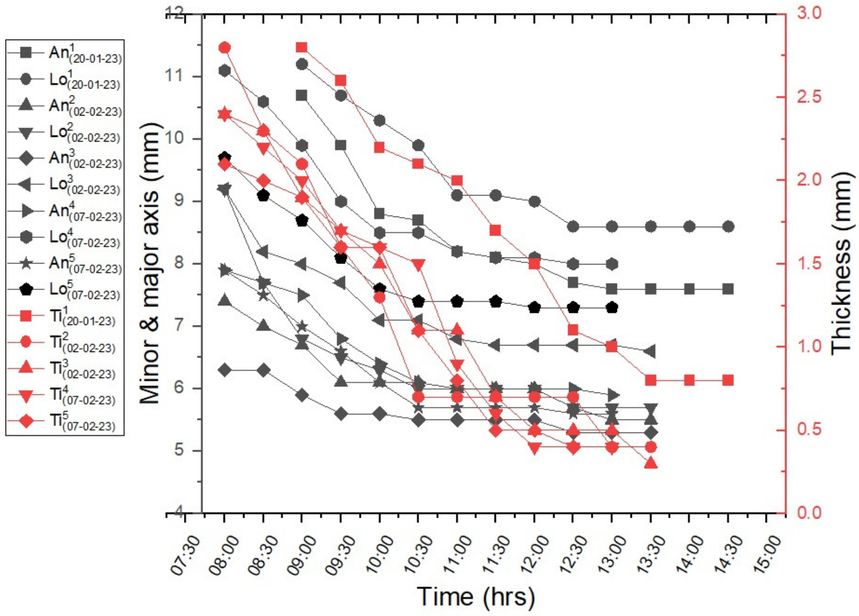

Figure 6. Thickness (Ti), minor axis (An), and major axis (Lo) of *Leucaena esculenta* samples. The superscript indicates the sample number according to Figure 2. The subscript represents the drying date.

During the drying process, we documented each sample's physical change in color through a series of images. As illustrated in Figure 7, all the samples shift from an initial apple green color to a moss green, eventually developing a flake-like texture and rough surface characteristics. This visual evidence demonstrates the effects of the drying process on the sample color, serving as a color comparison scale for selecting dry seeds during the drying process, with a noticeable change observed after 4 h of drying.

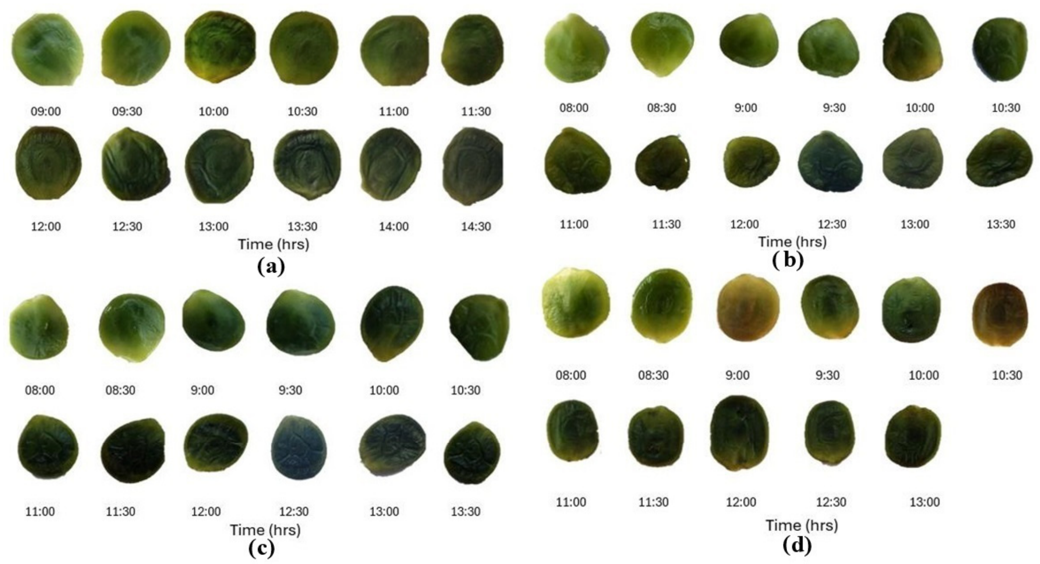

Figure 7. *Cont.*

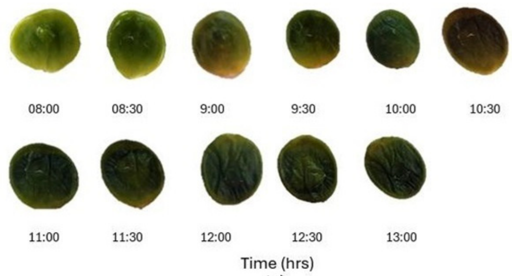

Figure 7. (**a**) Sample 1, drying time from 9:00 to 14:30 h. (**b**) Sample 2 and (**c**) sample 3, drying time from 8:00 to 13:30 h. (**d**) Sample 4 and (**e**) sample 5, drying time from 8:00 to 13:00 h.

3.3. Calculation of Weight and Moisture Loss

Before the drying process of *Leucaena esculenta*, the moisture content was determined using a moisture analyzer (VTSYIQI, Model: XY–110MW, Number: 1012204372). The results of the average moisture content of *Leucaena esculenta* from five samples is 63.78%. This moisture percentage was considered to construct the moisture (%) curves. Figure 8 shows the samples' weight loss (W) and moisture (M). The results show that for samples 2 $\left(W^2_{(02\text{-}02\text{-}23)} \text{ and } M^2_{(02\text{-}02\text{-}23)}\right)$, 3 $\left(W^3_{(02\text{-}02\text{-}23)} \text{ and } M^3_{(02\text{-}02\text{-}23)}\right)$, 4 $\left(W^4_{(07\text{-}02\text{-}23)} \text{ and } M^4_{(07\text{-}02\text{-}23)}\right)$, and 5 $\left(W^5_{(07\text{-}02\text{-}23)} \text{ and } M^5_{(07\text{-}02\text{-}23)}\right)$, both moisture loss and weight tend not to change significantly after 11:30 h.

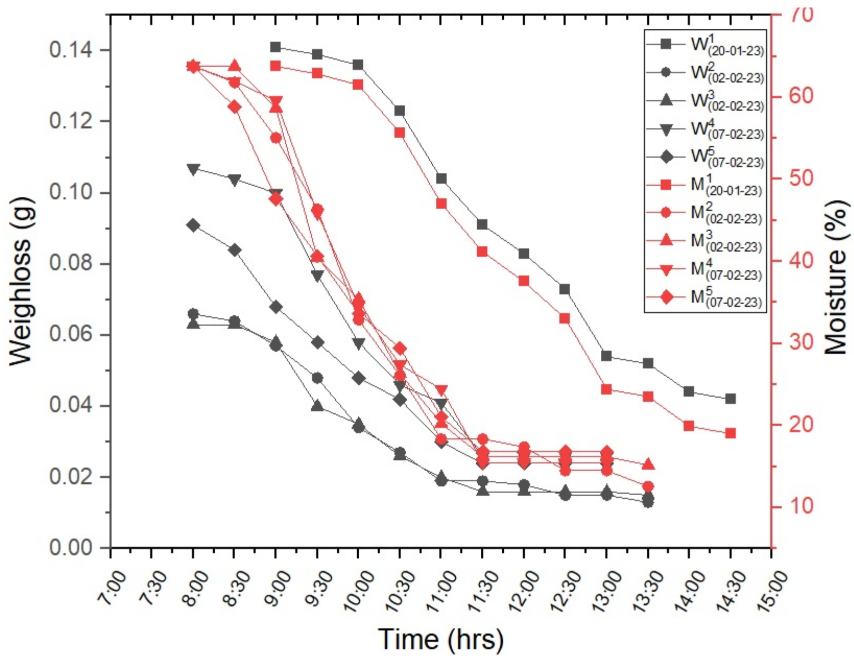

Figure 8. Weight and moisture loss of *Leucaena esculenta*. The superscript indicates the sample number according to Figure 2. The subscript represents the drying date.

However, sample 1 $\left(W^1_{(20\text{-}01\text{-}23)} \text{ and } M^1_{(20\text{-}01\text{-}23)}\right)$ changes in a small proportion after 13:00 h due to the coupled effect of the solar radiation and airflow speed, which vary more for this day versus the other days of the experiment (Figures 4 and 5). In effect, the air temperature is lowest inside the drying chamber; as a consequence, sample 1's out time is extended.

On the other hand, calculating water loss in food is closely tied to the effective diffusivity coefficient D_{eff}. This coefficient was calculated according to the Fick model, described in Section 2.3, and used effectively by some authors. The experimental data were fitted to Equation (3) to predict *Leucaena esculenta*'s drying kinetics accurately. The results of the effective diffusivity coefficients for samples 1–5 are shown in Table 2. As can be seen, the temperature profoundly impacts the drying kinetics. As the temperature increases, the diffusivity decreases due to a drop in speed despite the rise in temperature related to the high mass transfer resistance presented by the seeds. This relationship has significant implications and is essential for the design and operation of solar dryers that must be considered.

Table 2. Effective diffusivity coefficients in ($\frac{m^2}{s}$) for the thicknesses (mm) of samples 1–5.

Thickness	D^1_{eff}	Thickness	D^2_{eff}	Thickness	D^3_{eff}	Thickness	D^4_{eff}	Thickness	D^5_{eff}
2.8	9.906×10^{-8}	2.8	1.230×10^{-7}	2.4	8.252×10^{-8}	2.4	9.268×10^{-8}	2.1	6.256×10^{-8}
	8.541×10^{-8}		8.297×10^{-8}		7.579×10^{-8}		7.787×10^{-8}		5.674×10^{-8}
	6.115×10^{-8}		6.917×10^{-8}		5.172×10^{-8}		6.436×10^{-8}		5.121×10^{-8}
	5.572×10^{-8}		4.015×10^{-8}		4.140×10^{-8}		4.650×10^{-8}		3.631×10^{-8}
	5.054×10^{-8}		2.651×10^{-8}		3.224×10^{-8}		4.119×10^{-8}		3.631×10^{-8}
	3.651×10^{-8}		7.685×10^{-9}		1.734×10^{-8}		3.620×10^{-8}		1.716×10^{-8}
	2.843×10^{-8}		7.685×10^{-9}		1.734×10^{-8}		1.303×10^{-8}		9.078×10^{-9}
	1.529×10^{-8}		7.685×10^{-9}		7.020×10^{-9}		5.792×10^{-9}		3.546×10^{-9}
	1.263×10^{-8}		7.685×10^{-9}		3.582×10^{-9}		2.574×10^{-9}		3.546×10^{-9}
	8.086×10^{-9}		7.685×10^{-9}		3.582×10^{-9}		2.574×10^{-9}		2.270×10^{-9}
	8.086×10^{-9}		2.510×10^{-9}		3.582×10^{-9}		2.574×10^{-9}		2.270×10^{-9}
	8.086×10^{-9}		2.510×10^{-9}		1.289×10^{-9}				

4. Discussion

Nowadays, solar drying has been gaining importance as one of the techniques for food preservation because it guarantees the drying of products in regions of the world where solar radiation is abundant [33], such as in the State of Morelos in Mexico. It is necessary to consider some of the physicochemical properties of the products to be dried to guarantee the product's quality, such as the pH for this study, which is related to the quality of the seed. Although few studies on Leucaena leucocephala exist, most focus on production as animal feed [2,5,8,9,34]. Other authors comment that the seeds are used for human consumption, in preparing stews and sauces, and in medicinal use [5,7]. However, more studies related to drying in the literature are needed. Some studies only present data obtained from the pH of the gum [35] and the bark [36] extracted from Leucaena leucocephala, with values of 7.5 and 6.04, respectively. In this sense, these reported values allow us to have an approximation of the pH that the seeds must contain as part of the purpose of the study. Therefore, the pH values after the drying process approximate previously reported values (see Table 1).

On the other hand, the values of the effective diffusivity coefficient found in this study for each sample range between 9.906×10^{-8} and 8.086×10^{-9} $\frac{m^2}{s}$ (sample 1), 1.230×10^{-7}–2.510×10^{-9} $\frac{m^2}{s}$ (sample 2), 8.252×10^{-8}–1.289×10^{-9} $\frac{m^2}{s}$ (sample 3), 9.268×10^{-8}–2.574×10^{-9} $\frac{m^2}{s}$ (sample 4), and 6.256×10^{-8}–2.270×10^{-9} $\frac{m^2}{s}$ (sample 5). However, although they have minimal variation, it is attributed to the climatic conditions and product characteristics. Since there is no way to compare these parameters, there are studies on drying some legumes, such as green beans, which report effectiveness between 2641×10^{-9} and 5711×10^{-9} $\frac{m^2}{s}$ [28]. Likewise, in slices of green beans with values between 1.387×10^{-8} and 3.724×10^{-8} $\frac{m^2}{s}$ [30]. Other studies, such as alfalfa, report values from 9.13×10^{-14} to 1.06×10^{-9} $\frac{m^2}{s}$ [31], while for beans, between 10.8×10^{-10} and 67.0×10^{-10} $\frac{m^2}{s}$ [32]. Chickpeas range from 54.0×10^{-11} to 78.0×10^{-11} $\frac{m^2}{s}$ [37], and lentils range from 2.5×10^{-11} to 6.69×10^{-10} $\frac{m^2}{s}$ [38]. According to the literature, this study's diffusivity coefficient values are very close and equal for some legumes, such as green beans. However, for the other legumes, there is only an approximation.

Figure 9 shows a comparison of dried seeds (a) versus those that were subjected to the solar dryer process (b). The dried seeds were obtained from pods that dried naturally on the tree. As can be seen, when dried naturally, the seeds are brown, and the pH tends to decrease below 5.1. Seed color and acidity are two parameters associated with the seed quality for human consumption. However, no reports were found in the literature that validate these observations; this underscores the need for further research in this area.

Figure 9. Comparison of *Leucaena esculenta* seeds (**a**) by natural drying versus (**b**) solar dryer.

5. Conclusions

The Leucaena genus has received increasing interest recently as a potential energy source [39]. However, an integral approach to exploiting the species is necessary to make plantations economically viable. As there are no reported studies in the literature on the drying of *Leucaena esculenta* seeds that are used as a traditional food in many communities in central and southern Mexico; this study attempts to lay the groundwork for exploring its potential for human consumption by its use in conventional food in central and southern regions of Mexico. The drying kinetics yields diffusivity values comparable to similar processes for other seeds; these values are 9.906×10^{-8}–8.086×10^{-9} $\frac{m^2}{s}$ (sample 1), 1.230×10^{-7}–2.510×10^{-9} $\frac{m^2}{s}$ (sample 2), 8.252×10^{-8}–1.289×10^{-9} $\frac{m^2}{s}$ (sample 3), 9.268×10^{-8}–2.574×10^{-9} $\frac{m^2}{s}$ (sample 4), and 6.256×10^{-8}–2.270×10^{-9} $\frac{m^2}{s}$ (sample 5). The quality of the seeds was assessed through their acidity, with values reported of pH 6.34 and 5.98. 5.97, 5.82, 6.07, and color align with traditional selection parameters for human consumption.

However, further research is needed to establish solar drying as an ideal methodology for drying *Leucaena esculenta* seeds. Studies on the toxicity of the leaves and bark of Leucaena species are reported in the literature [40], but only recently have studies been reported on the profile of functional compounds in the seed [41], which gives more significant support to its use as human food. Potential pharmaceutical applications have also been explored [42], in line with its use in traditional herbal medicine in central and southern Mexico.

On the other hand, the indirect forced-flow solar dryer used by [29] remains promising in food drying, providing exemplary physical, chemical, and appearance characteristics, as reported in this study.

In a subsequent investigation, it is proposed that a study of the change in the organoleptic properties and nutritional elements of *Leucaena esculenta* before and after drying be conducted to continue guaranteeing the quality of the product. Moreover, studies on the consistency of color to count a comparative scale and rehydration capacity studies should be performed and compared with other drying methods.

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