Direct and mixed solar drying effect on edamame (Glycine max (L.) Merr.) kinetics and colorimetry

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Abstract

Edamame is food with valuable nutritional content, mainly due to its high protein and vitamin content. Given today's fast-paced lifestyle, dehydrated foods have become a significant option to obtain the necessary nutritional contributions. This study reports edamame drying in a mixed solar dryer (MSD) and a direct cabinet-type solar dryer (DSD). As quality parameters, colorimetric data, proteins, and initial and final water activity were obtained. According to the results, the equilibrium moisture content was reached faster in the MSD, with 6 hours; the maximum drying velocity achieved for this technology was 0.0109 kg water kg dry matter·min with a final moisture content of 0.6369 g water / g dry matter. In addition, the content and the total color change (ΔE) were improved in the MSD. The mathematical model that best adjusted to the experimental results in both technologies was the Weibull with a minimum R^2 of 0.9947. Solar drying is a feasible technology to conserve edamame, reduce greenhouse gas emissions, food waste, and provide essential nutrients to people's daily diet.

Keywords: Solar dryer, mixed solar dryer, thin layer modeling, colorimetric analysis, food preservation, edamame

1. Introduction

Edamame is the immature soybean (Glycine max (L.) Merrill), harvested as it reaches about 80% of its maturity. It has a yellowish-green color and differs from mature soybeans, usually light brown. (Fehr and Caviness, 1977). Most people have heard of edamame, especially in East Asia, because it provides many nutrients and generates medicinal effects on humans. It is rich in proteins, phosphorus, calcium, iron, vitamins, and dietary fiber; likewise, it prevents and suppresses various cancers due to its high content of isoflavones. Also, it can inhibit the activity of tyrosinase (Coward et al., 1993; Simonne et al., 2000), which causes skin spots that appear on the skin over time; Moreover, it has a positive impact on bone and dental health, reduces the risks of cardiovascular accidents and lowers blood cholesterol (Mentreddy et al., 2002).

Edamame is consumed mainly as a snack and vegetable, complement to soups, or processed into sweets. However, edamame has high water content, stimulating microorganisms' growth and proliferation. This condition results in fast decomposition, so its shelf life is only a few days. As a result, the FAO (Food and Agriculture Organization) data indicate that more than 20% of the harvested cereals is wasted, representing almost 50% of total food losses, generating the most significant contributor of greenhouse gas emissions. (UN and FAO, 2019).

Gradually, hunger and malnutrition are the primary health risk worldwide; around 135 million people suffer from severe hunger, and due to the COVID-19 pandemic, could double this figure and add 130 million more people by the end of 2020(UN and FAO, 2020). Likewise, along with famine, the poor diet of human beings is related. For example, in the last revision in 2018, about 821 million people worldwide suffered from malnutrition, 1 in 10 human beings (UN, 2020a). By 2019 the number of hungry people globally

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reached 690 million (47.7 million are from Latin America and the Caribbean). Similarly, 205 million people live in conditions with uncertainty about their ability to obtain food, which leads them to reduce the quantity or quality of the food they consume (UN, 2020b).

Given the current lifestyle, the growing demand for edamame worldwide, and its rapid decomposition, measures have been seeking to extend the shelf life. The main proposals to conserve edamame using different methods are a) Freezing by hydro-fluidization. In this method, concentrated aqueous solutions are used at low temperature as a cooling medium pumping it upwards through holes in the refrigeration vessel to generate jets of liquid that preserve the agitation of the refrigerant that creates high surface transfer coefficients (Fatahillah et al., 2019; Juan Manuel Peralta, 2009). b) Blanching in mesh bags in hot water (at 100°C) combined with cooling storage (4°C) or freezing (-20°C) (ChunQuan et al., 2012). c) Freezing drying or lyophilization combined with the bleaching with a steam of the fresh edamame(Kamila et al., 2019).

However, dehydration is an efficient method to remove water by evaporation from most products. The reduction of moisture content inhibits and decreases microbial and enzymatic activity, advantageous for long-term preservation. Few have studied the conservation of edamame using dehydration methods, as in Qing-guo et al. (2006). They used microwave drying, vacuum with pulse jet, vacuum, and hot air drying to determine the microstructure, color, texture, and taste of edamame; Also, Hu et al. (2007) conducted vacuum microwave drying (VMW) to investigate and compare drying velocity, final moisture content, and dry product quality between the different heights of edamame in a deep bed. However, these works used conventional technologies with high energy consumption and high costs for their use.

Despite a large amount of information on the freezing of edamame using various methods, the information related to drying or dehydrating is scarce. In addition, there is a lack of studies on drying using solar energy. It is important to remember that developing energy-efficient technics is essential to solving complex environmental problems (Castillo-Téllez et al., 2020).

2. Methods

Raw material

Immature soybeans (Glycine max (L.) Merr.), grown in northern China, near the border with Russia, were selected. First, the edamame beans were separated to obtain a homogeneous group, depending on the size and color. Then, they were washed and weighed. The weight of each bean ranged from .95 to 1.00 grams. The experimentation was performed during three sunny days with very casual small clouds in Xochitepec, Mor., México. The experiment was carried out in triplicate.

In this work, the drying process of the edamame was carried out experimentally using a cabinet dryer and a mixed-type solar dryer.

Direct solar dryer cabinet type

The equipment consists of: a drying chamber of 44 liters with measures of 35x64x26 cm with transparent polycarbonate cover, two aluminum trays with .30 m^2 of total drying area, humidity (%) and temperature sensors (°C) and inside the drying chamber a perforated tray with an area of 0.0468 m^2 was placed. Heat transfer was by natural convection.

Fig. 1 Direct solar dryer

Mixed solar dryer

The MSD contains three main parts: 1) A flat solar collector heating the air by natural convection, 2) a drying chamber of 0.038 m^3 with eight trays located in 4 vertical levels. The total drying area is 0.52 m^2, allowing solar radiation passage through a transparent polycarbonate cover. Its side walls are insulated with a polyisocyanurate plate 1.27 cm thick. 3) A chimney where moist air from the drying chamber can be extracted (López-Vidaña et al., 2020).

Fig. 2: Mixed solar dryer

Instrumentation

Operation parameters

Humidity: To determine the moisture of edamame beans, two moisture analyzers, Sartorius MA 45 and Ohaus MB45, were used with an accuracy of ± 0.01% mg. The sample of approximately 1 gram was placed in the analyzer. This procedure was performed before starting and at the end of drying.

Water activity (a_w): Water activity is the parameter that determines the stability of the food concerning ambient humidity, and the fresh and dry edamame was measured before and after the drying process. A portable computer, Rotronic HygroPalm, was used with an accuracy of ± 0.01%. Mg. An average of three measurements was reported at room temperature of 26.5 ± 1°C).

Temperature: It was measured by type K thermocouple, previously calibrated using an Ameter Jofra Instruments temperature calibrator, model D55SE, in a range of 10°C to -12°C and accuracy of ± 0.04°C.

Weight: Weight measurements were determined by Ohaus' Adventure balance model with an accuracy of ± 0.001 grams.

Colorimetry: A colorimeter model PCE-CSM 5 previously calibrated for high-precision quality control using the CIELAB color space was used.

Mathematical modeling

The models applied in this study are shown in Table 1. The dimensionless MR (moisture ratio) is a function of drying time and is calculated as (Toĝrul and Pehlivan, 2004):

$$MR = \frac{M_c - M_e}{M_0 - M_e} \qquad \text{(eq. 1)}$$

Where Mc is the moisture content, Me is the equilibrium moisture content, and Mo is the initial moisture.

The equilibrium moisture content Me was determined by the equation y, (Castro-Muñoz and Nieves-Segura, 2018):

$$Me = \frac{W_1 Mo + W_f W_1}{W_1(1 - M)} \qquad \text{(eq. 2)}$$

M_e, expressed in (kg water/kg dry matter), W_1 is the initial weight, M_0 is the initial moisture of the samples, and W_f is the weight of the sample at M_e.

This ratio was adjusted to the five thin layer drying models shown in Table 1. The model that best describes the experimental data was analyzed according to the Root Mean Square Error (RMSE), chi-square (χ^2), and correlation coefficient (R^2).

Tab. 1: Thin-film models applied to dry kinetics.

Name	Model	Reference
Newton	$MR = exp(-kt)$	(Liu and Bakker-Arkema, 1997)
Page	$MR = exp(-kt^n)$	(Page, 1949)
Modified Page	$MR = exp(-(kt)^n)$	(White et al., 1981)
Henderson and Pabis	$MR = a\ exp(-kt)$	(Henderson and Pabis, 1961)
Logarithmic	$MR = a\ exp(-kt) + c$	(Toğrul, 2005)
Wang y Singh	$MR = 1 + at + bt^2$	(Wang and Singh, 1978)
Weibull	$MR = exp\ (-{}^{t}/_{\beta})^{\alpha}$	(Tzempelikos et al., 2015)

3. Results and discussion

Samples' initial moisture content was 70% and water activity (a_w) of 0.95. At the end of drying, the water activity decreased to 0.35, which ensures the safety of the food. The maximum ambient temperature and humidity reached 37 °C and 70% in the experimentation days, respectively. The DSD reached a temperature of 59 °C inside the drying chamber, while the MSD reached 78 °C and minimum humidity of 25% and 12%, respectively (Figure 3).

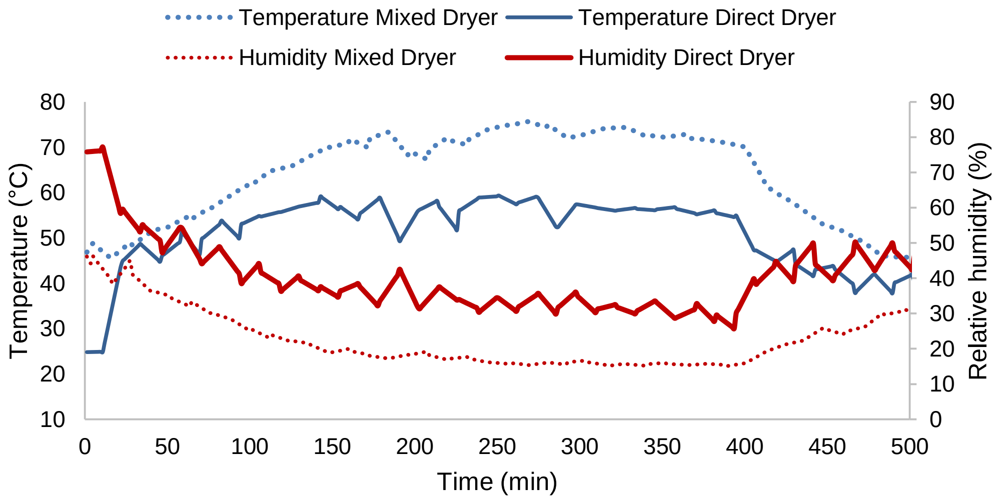

Fig. 3: Temperatures and Relative humidities reached in dryers

Higher temperatures and lower relative humidity are essential factors to reduce drying times, providing adequate conditions to facilitate moisture extraction from the food (Jorge de Jesús et al., 2021).

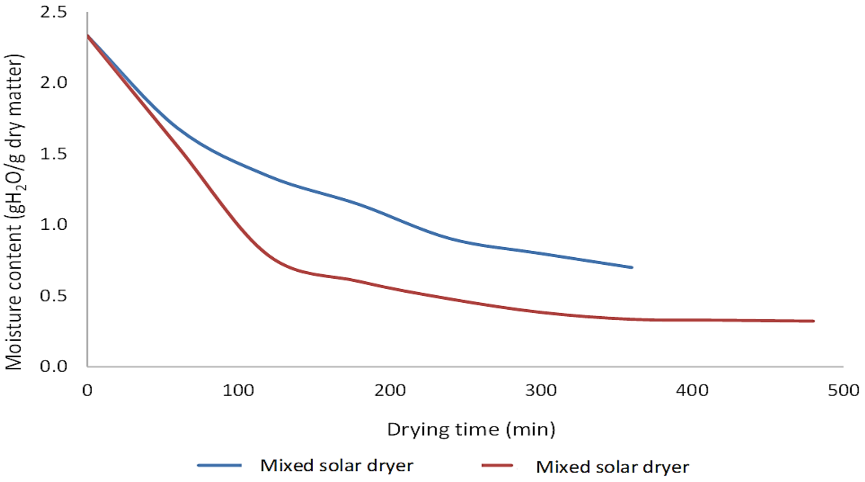

Fig. 4: Moisture content evolution during drying

The moisture content was recorded during edamame drying. In Figure 4, the moisture content reduction during the drying kinetics can be observed. The graph shows that the MSD minimizes the time to reach equilibrium moisture content (the vapor pressure of the water held by a product is equal to the water vapor pressure of the surrounding air (Yaciuk, 1981)). In this dryer, only 380 min was required to finish the drying. On the other hand, the DSD needed 490 min. This time reduction is due to the higher temperatures and humid conditions inside the MSD chamber, allowing the drying process to be more efficient and consequently helping producers obtain higher economic profits.

The drying rate curves did not show any period of constant velocity in the DSD, while, in the MSD, an increase in the rate can be observed towards the end of the kinetics. Even though at the beginning of the kinetics, the drying velocity was higher in the DSD, the slope of the drying velocity curve of the MSD remained more constant during the process. (See Fig. 5)

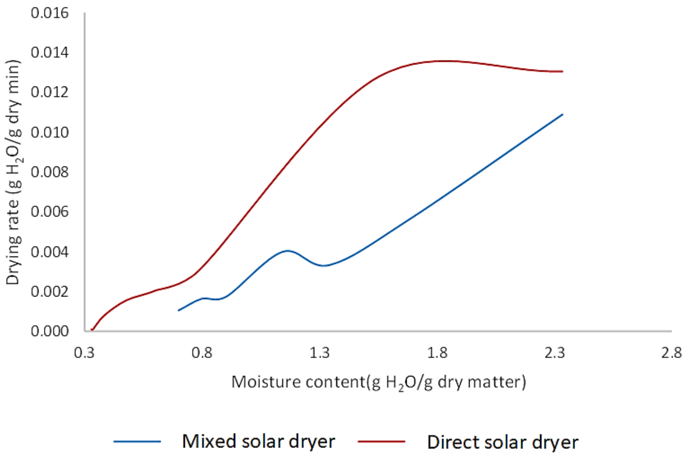

Fig. 5: Drying rates of edamame, with both technologies.

Figure 6 shows the moisture ratio (MR) versus the drying time. The solid lines correspond to both solar technologies' experimental results (MR). As can be seen, most of the models present a good fit with these results. However, the mathematical that best represents all cases' experimental results, with an $R^2 > 0.99$, is Weibull. Therefore, this model can predict the kinetics of solar drying of edamame under experimental conditions.

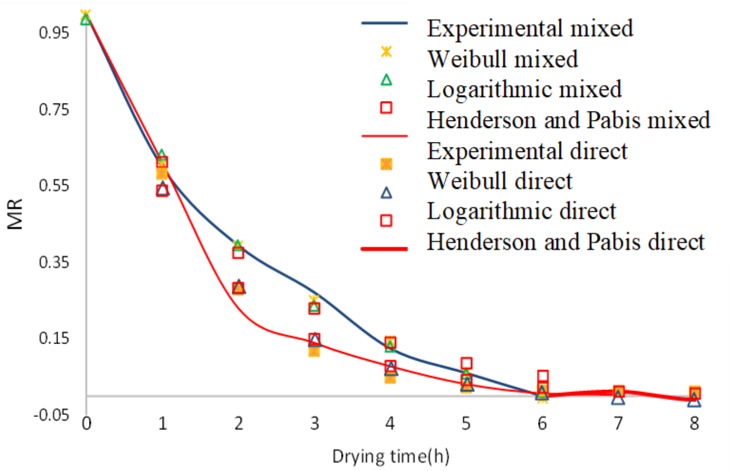

Fig. 6: Drying adjustment charts for both technologies

Table 2 shows the adjustment parameters and statistical data obtained for all analyzed models. Results illustrate that the best model describing edamame kinetics is Weibull for both experimental technologies because it presents higher R^2 and minimum X^2 and RMSE. Consequently, this model can be used to predict edamame drying.

Tab. 2 Modelling parameters

Direct Solar Dryer			**Mixed Solar Dryer**		
Weibull	a	1.20E-02	Henderson and Pabis	a	1.6393
	b	-1.3083		k	0.4921
	k	0.2746		R^2	0.9921
	n	1.5965		RMSE	0.0292
	R^2	0.9947		X^2	0.0012
	RMSE	0.0236	Weibull	a	-0.9769
	X^2	0.0010		b	-8.5077
Logarithmic	a	1.9079		k	1.4603
	c	-1.76E-02		n	0.2035
	k	0.6111		R^2	0.9988
	R^2	0.9913		RMSE	0.0115
	RMSE	0.0304		X^2	0.0003
	X^2	0.0012		a	1.6019
Henderson and Pabis	a	1.9429	Logarithmic	c	-8.40E-02
	k	0.6428		k	0.4026
	R^2	0.9904		R^2	0.9965
	RMSE	0.0320		RMSE	0.0192
	X^2	0.0013		X^2	0.0006

Table 3 shows *a*,*b*, and L parameters before and after the procedures. During the drying process, these parameters changed depending on the dryer used. It can be seen that solar drying presents good color preservation in edamame.

Tab. 3 Color change in both technologies

LAB	Fresh edamame	Direct Solar Dryer	Mixed Solar Dryer
L*	40.04	50.69	48.9
a*	-4.65	1.43	2.36
b*	19.33	23.5	19.11

As shown in Figure 7, the ΔE is very similar in both cases and very close to the commercially accepted values. However, the Chroma is higher on the DSD. Therefore, the MSD preserves better edamame color because prolonged exposure to sunlight decreases the product's quality in the DSD. However, a significant difference in ΔE is not desirable because consumers prefer products that resemble the color of the fresh product before drying. In addition, a considerable color difference shows a higher degree of browning, which could be unattractive in appearance. According to the literature, when the final product has a value of up to 3, the color difference results appreciably (Hii and Law, 2010). Moreover, as the color change between raw and dry products is more significant, nutrients' degradation is higher.

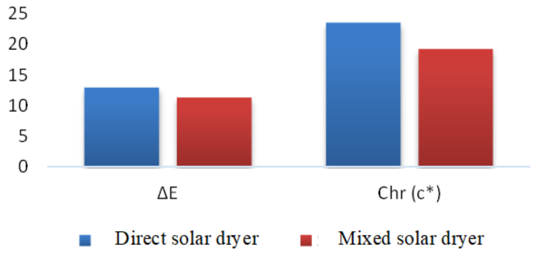

Fig. 7: Delta E and resulting Chroma in both technologies.

4. Conclusions

Two solar drying technologies were applied to edamame preservation. The results show that both technologies are technically feasible for this process. In addition, the kinetics, colorimetry, and models during edamame drying were analyzed. According to the findings, the hybrid solar dryer technology provided a shorter drying time, higher drying rates, and better color preservation. The drying time needed to reach equilibrium moisture for the MSD was 380 min with an ΔE value of 11.03, which is commercially acceptable. However, DSD can be used with competitive results.

Moreover, the Weibull model was better adjusted to the drying kinetics. Therefore this model can be used to design and size solar dryers. Solar drying is a sustainable solution for edamame conservation.

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