



Obtaining of *Crataegus mexicana* leaflets using an indirect solar dryer

Obtención de hojuelas de tejocote mediante secado solar indirecto

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Abstract

Drying behavior for ripe and unripe *Crataegus mexicana* was studied for an indirect solar dryer in order to obtain the effective diffusion coefficients (D_f). The behavior of the drying process was examined, observing a significant effect related to the ripeness degree of the fruit. The effective diffusion coefficients were $5.698 \times 10^{-10} \text{ m}^2/\text{s}$ and $5.993 \times 10^{-10} \text{ m}^2/\text{s}$, for unripe and ripe *Crataegus mexicana*, respectively. Solar drying is a viable alternative for adding value to the production of this fruit in central México.

Keywords: Drying kinetics, solar dryer, effective diffusivity, *Crataegus mexicana*.

Resumen

Se estudió el comportamiento de secado para la especie *Crataegus mexicana* madura e inmadura por un secador solar indirecto para obtener los coeficientes de difusión efectiva (D_f). El comportamiento del proceso de secado fue examinado, observando un efecto significativo relacionado con el grado de madurez de la fruta. Los coeficientes de difusión efectiva (D_f) fueron de 5.698×10^{-10} and $5.993 \times 10^{-10} \text{ m}^2/\text{s}$, para la *Crataegus mexicana* inmadura y madura, respetivamente. El secado solar es una alternativa viable para agregar valor a la producción de esta fruta en el centro de México.

Palabras clave: Cinética de secado, secador solar, difusividad efectiva, *Crataegus mexicana*.

1 Introduction

Crataegus mexicana is one hawthorn species among the approximately 200 reported worldwide (Ulna and Sacilik, 2011). The fruit is used as pectin source for food, cosmetics, pharmaceutical, and textile applications. However, there are mainly consumed as part of the traditional Mexican cuisine and as remedy for herbal medicine preparations. Drying is one of the oldest methods used to preserve human's foods. Fruits and vegetables are dried to inhibit microbial enzymatic activity and foodstuff decay. As a result of reduced water availability on the dried material, the physical and chemical changes are minimized during the storage, thus increasing shelf life. Also, transportation and storage costs are reduced by weight

and volume lowering on the dried products (Dadali *et al.*, 2007; Doymaz and Ismail, 2011).

Many feedstocks cannot be harnessed to their full potential due to reduced production times for ripeness and limited shelf-life. That is why countries are looking for new alternatives; energy friendly feedstock processing that adds value to the crops (Kamenan *et al.*, 2009).

An alternative to the drying process of fruits and vegetables is through renewable energy sources such as solar irradiation. In many parts of the world the sun provides radiation that allows one to take advantage of it approximately 12 hours during the day. Solar energy for drying applications is preferable because it is abundant, free, inexhaustible and non-polluting (Kamenan *et al.*, 2009).

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Crataegus mexicana is a temporal crop in central Mexico, with limited economical value. It usually grows wild, in slopes and other terrains unsuitable for other crops and, processing suitable ripe and unripe fruit alternative processing, may provide opportunities to develop applications such as in tea or in formulating mixtures for traditional Mexican beverages (so-called “ponche”). For this case, solar drying is sought as post harvest alternative processing allowing the formulation of new added value products. Here the drying kinetics of the ripe and unripe *Crataegus mexicana* fruit was investigated, seeking to establish a first-principles foundation for the modeling and subsequent scaling for indirect solar dryers design.

2 Materials and methods

2.1 Materials

Forty commercially considered ripe and unripe samples of *Crataegus mexicana*, were recolected from Hueyapan Morelos, Mexico, latitude 18.900° N and longitude -98.670° W. The samples were collected during the 2016 Harvest. The months of November and December of each year are considering the best harvest time. The products were disinfected, washed and dried with absorbent paper before being stored in a freezer at 4°C until processing.

The selection of ripe and unripe *Crataegus mexicana* were obtained using the experience of the harvesting people how select the fruit based on their skin color. Such experience was translated to a color match scale in order to select the fruit.



Fig. 1. Color scale for ripeness classification, ripe *Crataegus mexicana*: From left to right shows skin color levels: 0 to 4.



Fig. 2. Color scale for ripeness classification, unripe *Crataegus mexicana*. From left to right shows skin color levels: 0 to 4.

For experiments were calculated the pH, sugar content ($^{\circ}\text{Brix}$), moisture content, weight loss, in order to estimate the effective diffusivity of the fruit. Clearly ripe and unripe fruits were used for the experiment (arbitrary scale value of 4 on Fig. 1 and 2).

Before processing, the products were removed from the freezer at 4°C and cut in 3mm thickness slices. The pH and sugar content ($^{\circ}\text{Brix}$) were measured using a pH meter (HANNA, HI 84532-02) and ATC refractometer (MPN: 43217-71864) respectively, as shown in Fig. 3 and 4. In Figure 3 no significant differences can be observed between ripe and unripe samples for sugar content, reporting values in the range 3 - 3.1 $^{\circ}\text{Brix}$, While, in the Figure 4 it is showed that for the pH of the same samples likewise no significant differences are observed, with values in the range 3.5 - 3.7.

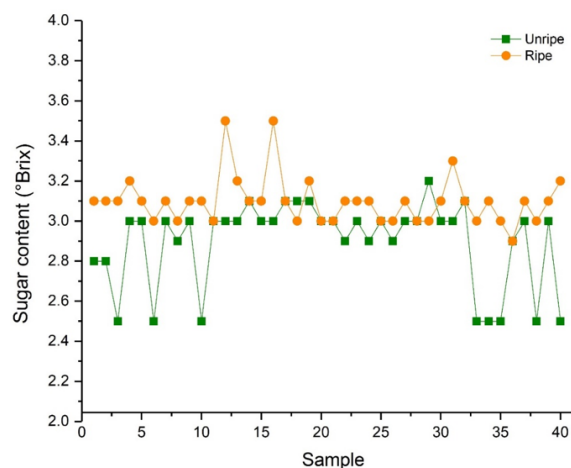


Fig. 3. Sugar Content ($^{\circ}\text{Brix}$): ripe and unripe *Crataegus mexicana*.

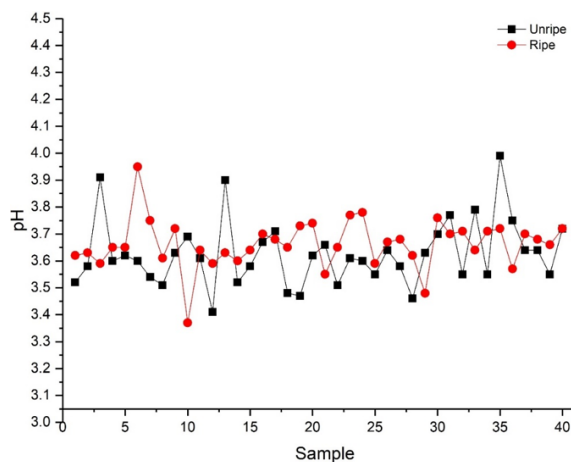


Fig. 4. pH: ripe and unripe *Crataegus mexicana*.

2.2 Experimental set-up

The outdoor drying experiments were performed in Technological Institute of Zacatepec from Morelos México, on December 2016, with latitude and longitude of 18.653° LN and -99.184° LW, respectively. The indirect solar dryer used in this experiment consisted of two parts: drying chamber and solar collector. A scheme is shown in Fig. 5.

The products were introduced in the drying chamber. The chamber was built in stainless steel. Chamber size is: 101 x 45.5 x 127 cm, as shown in Fig. 6.

Three drying trays were used and were placed horizontally with 7 cm between each other. The drying chamber can accommodate up to 15 trays. The trays were built form aluminum frame and nylon mesh. Trays size is 88 x 41 cm, as shown in Fig. 7.

Temperatures was measured into the drying chamber with a DHT22 sensor and stored in the computer through a microcontroller (Arduino Mega). Temperature measurements have a $\pm 0.1^\circ\text{C}$ precision.

Drying air was introduced to the drying chamber by forced convection. Drying air was forced into the chamber by two fans (NMB, 12 V, 0.3 A). Air flow velocity was controlled at 0.7 m/s as measured by an anemometer (AMPROBE TMA-10A, range 0.40 to 25 m/s).

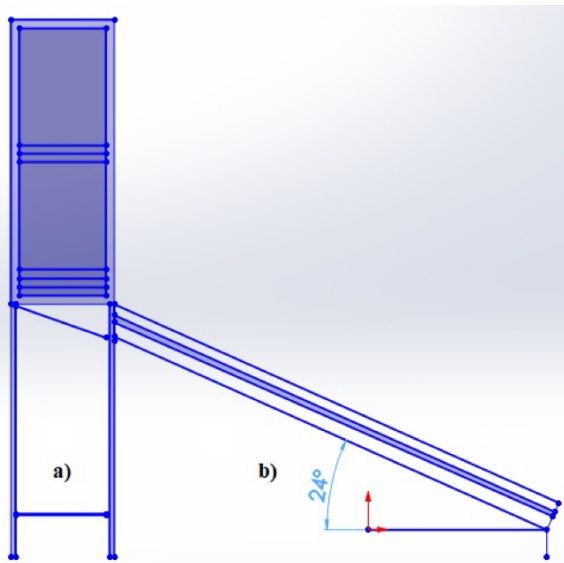


Fig. 5. Indirect solar drying: a) drying chamber. b) solar collector.

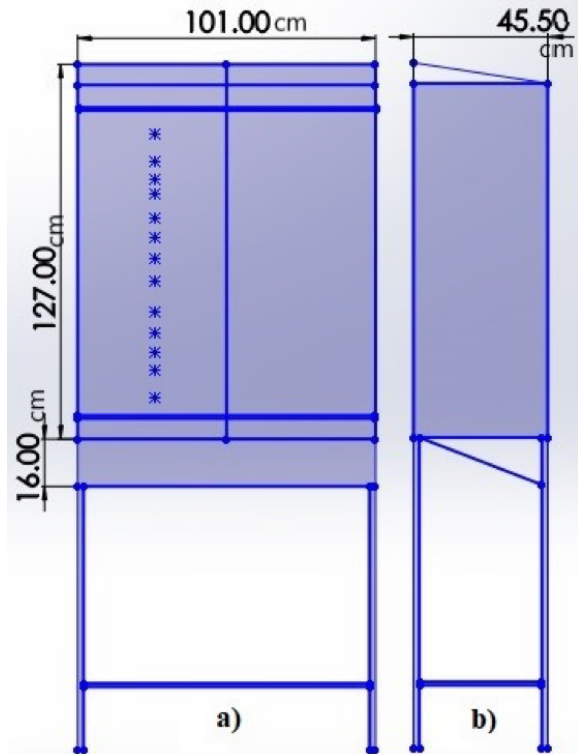


Fig. 6. Drying chamber dimensions: a) front view, b) lateral view.

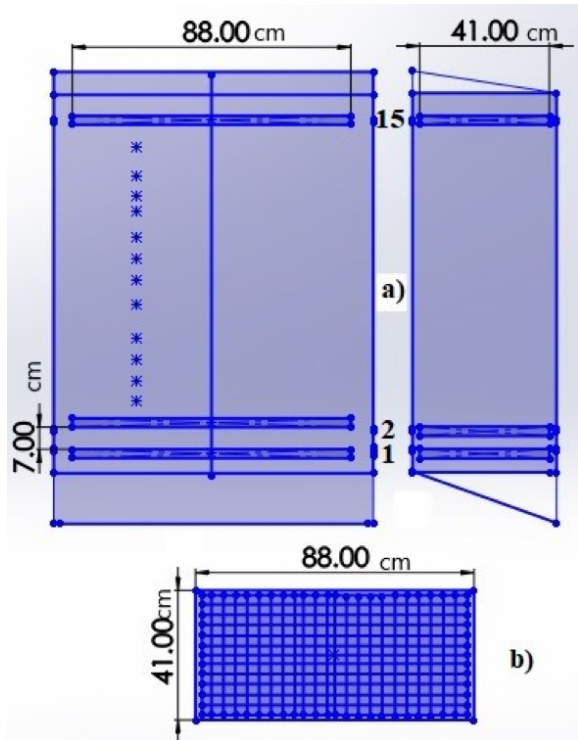


Fig. 7. Drying Chamber: a) drying trays, b) tray size.

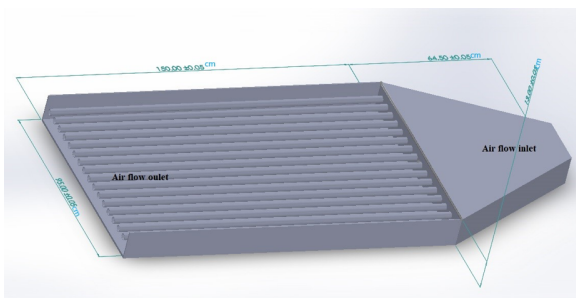


Fig. 8. Indirect solar collector. Air flow track, the air flows right to left.

The solar collector size is 214.5 x 95 x 13 cm. Solar collector was oriented to the south with a 24° slope, as shown in Fig. 8 and 5. It was built of stainless steel with clear acrylic cover, and black mate pipes to absorb the solar radiation during the day. It includes an aluminum sheet below the pipes to reflect solar radiation and polyurethane foam 3 cm thickness for thermal insulation, in order to reduce outward heat loss.

2.3 Mathematical modeling of drying curves

In the process drying, the effective diffusion coefficients were experimentally obtained and simulated using Fick's model. Fick's diffusion equations were solved considering an evenly distributed of the moisture throughout in sample mass, mass transfer is symmetric to the center, equilibrium between moisture surface and surrounding air; negligible mass transfer resistance at the surface as compared to internal resistance of the sample; mass transfer takes place by diffusion; diffusion coefficient is constant and shrinkage is negligible (Bal et al., 2010; Crank, 1975). Under these assumptions and premise, the solution of the Fick's diffusion equation is given by Eq. (1): (Bal et al., 2010; Wang et al., 2007; Di Scala and Crapiste, 2008; Ramesh et al., 2001; Pezzutti and Crapiste, 1997):

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n - 1)^2} \exp\left[-(2n-1)^2 \frac{\pi^2 D_{eff} t}{2L^2}\right] \quad (1)$$

here, M stands for moisture content at a specific time, M_0 for initial moisture content, M_e for equilibrium moisture content ($\frac{kg \text{ water}}{kg \text{ dry mass}}$), D_f for effective diffusion coefficient (m^2/s), L for the half thickness of leaflets (m) and t for drying time (min).

For long drying times, Eq. (1) can be simplified by taking the first term as shown in Eq. (2):

$$\frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{ft}}{4L^2}\right) \quad (2)$$

Eq. (2) can be also written in a logarithmic form as follow:

$$\ln\left(\frac{M - M_e}{M_0 - M_e}\right) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{ft}}{4L^2} \quad (3)$$

Effective diffusion coefficient is predicted by calculating the slope from the drying time versus experimental values of logarithmic moisture ratio ($\ln(MR)$). It can be seen that the plot is a straight line in the graph between drying time (t) and $\ln(MR)$ of Eq (2), and slope of this straight line is calculated by Eq. (4) (Vega et al., 2007).

$$\frac{\pi^2 D_{ft}}{4L^2} \quad (4)$$

In this context, the effective diffusion coefficient in the drying process usually depends on composition, moisture content, temperature, the type of the material and the equipment size. If the contact area for the drying chamber is bigger than the solar collector area, the solar collector will not be able to provide the desired airflow and target temperature for the drying process.

3 Results and discussion

Before studying the drying process, initial moisture content of ripe and unripe *Crataegus mexicana* was determined through weight loss using the Eq. (5) and finding values of 78.01 y 79.81%, respectively. For this, the Ohaus MB45 moisture analyzer was used at 100 °C.

$$M_e = \frac{\text{wet weight of the sample}}{\text{weight of the sample after drying}} \quad (5)$$

Moisture content loss of product in leaflets form is shown in Fig. 9, which depends on drying time and temperature, as show in Table 1.

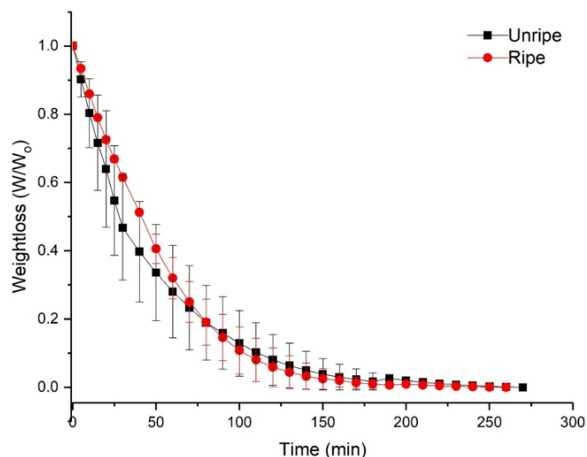


Fig. 9. Weight loss between ripe and unripe *Crataegus mexicana*.

Table 1. Drying temperatures inside drying chamber, of ripe and unripe *Crataegus mexicana*.

Time (hr)	Ripe: T (°C)	Unripe: T (°C)
9:00	34	33
9:30	39	38
10:00	49	48
10:30	53	53
11:00	55	54
11:30	55	54
12:00	59	58
12:30	60	58
13:00	62	61
13:30	61	61
14:00	62	61
14:30	56	55
15:00	57	58
15:30	57	57
16:00	55	56
16:30	51	52
17:00	49	49

The experiments were repeated four times in order to estimate the experimental error. The drying curves are shown in Fig. 10 and 11. As can be observed, the drying kinetics of ripe and unripe *Crataegus mexicana* exhibit an exponential loss during the first 5 hours of drying, reaching asymptotically a stable final weight after this time. Both Figures, show rapid water loss at the beginning of the drying process. Water content loss is variable during the experiment due to the variation in temperature induced for the variable solar radiation during the day. This event occurs

when higher air temperatures produce higher drying velocity (Holdsworth, 1986), due to the corresponding increase in heat transfer convection coefficient. Results showed that in order to complete the drying process of products in leaflets form up to 5 hours drying are necessary with the temperatures showed in Table 1. Thereby, reducing the moisture content below 20% is achieved, from its initial value of 78.01 and 79.81% for ripe and unripe fruits, respectively. Also, in general, one expected the ripe fruit to be sweeter and with lesser acidity than the unripe fruit, however, for the samples studied here, no significant differences were observed (95% confidence interval), probably due to the nonuniform distribution on the genetic variety of the trees and uneven cropping conditions.

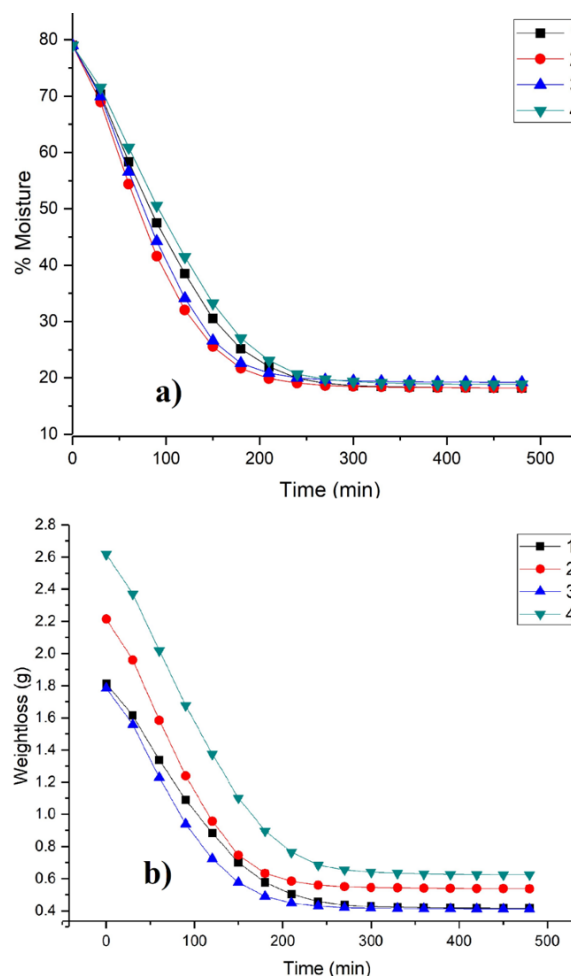


Fig. 10. a) Moisture ratio loss (%). b) Weight loss (g) vs time (min). Four independent ripe samples (1, 2, 3 and 4) are presented.

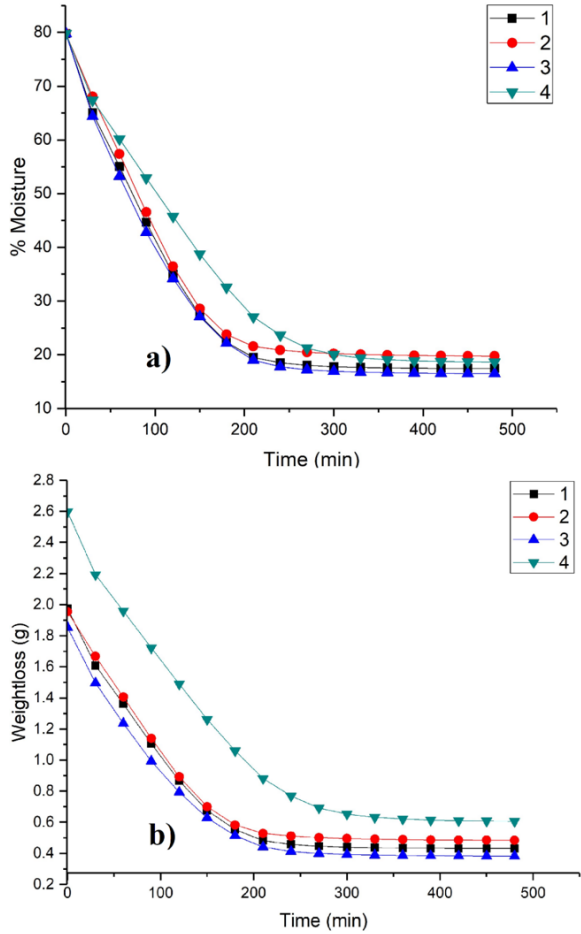


Fig. 11. a) Moisture ratio loss (%). b) Weight loss (g) vs time (min). Four independent unripe samples (1, 2, 3 and 4) are presented.

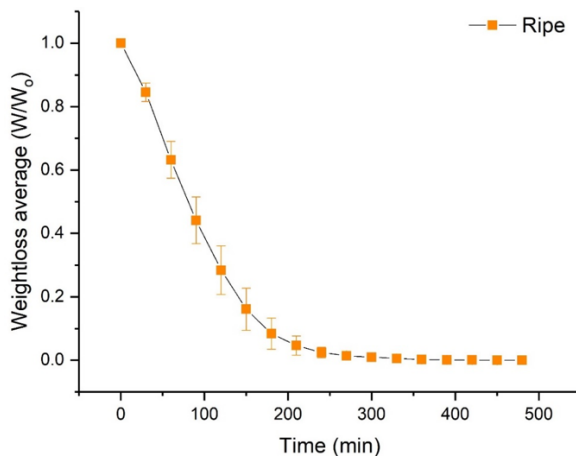


Fig. 12. Weight loss average for ripe samples.

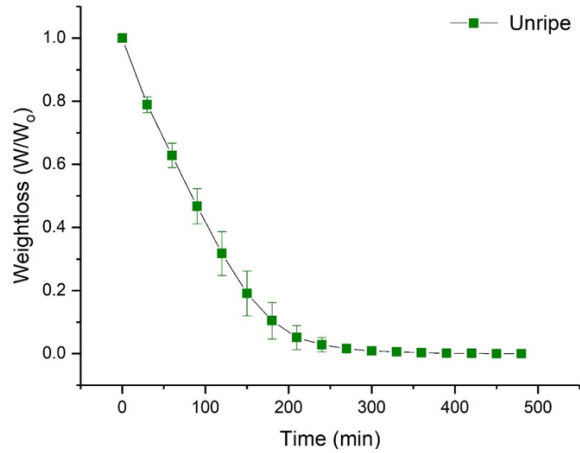


Fig. 13. Weight loss average for unripe samples.

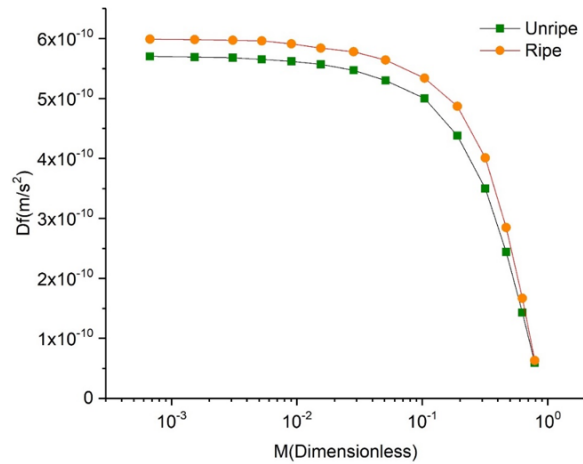


Fig. 14. Diffusivity of ripe and unripe *Crataegus mexicana*.

The weight loss averages for ripe and unripe fruits are shown in Figs. 12 and 13, respectively. Here, again, it can be observed that after approximately 5 hours of processing the moisture stabilizes asymptotically.

The diffusivity coefficient D_f is an effective diffusivity that encompasses effect of several phenomena affecting water loss. Its value is always calculated through mathematical models adjusting experimental data. As diffusivity may vary according to the drying conditions, it is not intrinsic to a material. Therefore, through Fick's models of diffusivity, neglecting sample shrinkage, drying kinetic predictions can be achieved. Also, at higher drying temperatures higher drying velocity is found,

because temperature increase favors mass transfer and effective diffusivity increases. Now, when the moisture ratio increases in the products, internal mass transfer resistance decreases. At lower moisture content, interstitial spaces increase in the *Crataegus mexicana* structure, facilitating water removal. Thus, the average effective diffusivity was found to be: $5.698 \times 10^{-10} \text{ m}^2/\text{s}$ and $5.993 \times 10^{-10} \text{ m}^2/\text{s}$, for ripe and unripe *Crataegus mexicana*, respectively, as show in Fig. 14.

Also, it can be observed that the drying kinetics of ripe-unripe *Crataegus mexicana* have similar characteristics as those exhibited by tropical fruits. Likewise, the effective diffusivities obtained here compared favorably with other studies involving tropical fruits, for examples: Flores-Martínez *et al.* (2018), have performed the study of the diffusion of the essential oil of pimento with of effective diffusivity values are between 3.7980×10^{-11} to $5.2578 \times 10^{-10} \text{ m}^2/\text{h}$. Also, Saxena and Dash, 2015, studied the drying kinetics of ripe jackfruit pulp in thin layers of approximately 3 mm thickness to allow full exposure of hot air in the drying chamber using a laboratory tray dryer for air temperatures of 50, 60, 70 and 80°C. The initial moisture content of the pulp was 77.56%. They obtained a diffusivity of $4.56 \times 10^{-10} \text{ m}^2/\text{s}$ at 80 °C and diffusivity of $1.264 \times 10^{-10} \text{ m}^2/\text{s}$ at 50°C. Thus, Sampaio *et al.* (2017) modeled of the osmo-convective drying kinetic and determine the effective mass diffusivity coefficient of Persimmon fruits. the initial moisture content of the persimmon fruits was 83 g of H₂O/g dry matter. The fruit was subjected to osmo-convective drying at three different temperatures (50, 55, and 60 °C). The effective mass diffusivity coefficients were 1.04×10^{-6} , 1.40×10^{-6} , and $8.27 \times 10^{-7} \text{ m}^2/\text{s}$ at 50, 55, and 60 °C, respectively.

Also, Uribe *et al.* (2011) studied he behavior of the drying kinetics of pepino fruit at five temperatures (50, 60, 70, 80 and 90 °C). The average initial moisture content of pepino fruit samples was $0.910 \pm 0.009 \text{ g water g}^{-1}$. The pepino fruits were cut in leaflets of $4.0 \pm 0.2 \text{ mm}$ in thickness. The effective mass diffusivity coefficients were 2.55×10^{-10} to $7.29 \times 10^{-10} \text{ m}^2/\text{s}$. Also, Rayaguru and Routray, 2012, investigated drying kinetics of stone apple slices of thickness of 8 mm. The slices were dried at four different air temperatures of 40, 50, 60 and 70°C in an experimental convective tray dryer. They presented the effective moisture diffusivity values between 3.7317×10^{-10} to $6.675 \times 10^{-10} \text{ m}^2/\text{s}$.

Conclusions

Although, some experimental values observed for other fruits can be a little different, due moisture content, temperature, and material structure, as well as the drying equipment used different. Such as, Ventura-Cruz *et al.* (2019). Even so, the *Crataegus mexicana* has effective diffusion coefficients and drying time similar with any of them.

Finally, such as is presented for Serdar and Vildan (2016). They investigated the thin layer drying characteristics of hawthorn fruit. This last kind of fruit is of the same variety as *Crataegus mexicana*. The drying kinetics processes were carried out at three temperatures of 50, 60 and 70 °C and air velocities of 0.5, 0.9 and 1.3 m/s, using a convective dryer. they found effective diffusivity values of $2.34 \times 10^{-10} \text{ m}^2/\text{s}$ to $2.09 \times 10^{-9} \text{ m}^2/\text{s}$, that, values that are very similar to the ones found in this study. As summary, the indirect solar drying used here, appears to be a good option in drying of tropical fruits.

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