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Cost analysis of drying process by studying its kinetic parameters: A new study in Mexican chillies

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Abstract: The drying process of vegetables is a widely used technique for food conservation. However, this process can be expensive, and the cost highly depends on the ventilation, drying temperature and drying characteristics of the chillies. The contribution of this new study was to obtain the drying kinetics parameters of two different types of Mexican *Capsicum annuum* (Puya and Mulato) and model it at different temperatures with two different ventilation levels. The aim of this study is to provide a method to analyse the cost of the drying process by studying its drying kinetics parameters. The experimental results were fitted to Weibull distribution and Newton's model, obtaining an adequate numerical fit at different drying temperatures. The Weibull distribution demonstrates to be a better fit than Newton's model. Drying kinetics parameters were also studied by a diffusive model with effective diffusivity. The effect of temperature on the diffusivity was described by the Arrhenius equation with activation energy of 49.7 kJ mol^{-1} for Puya and 24.1 kJ mol^{-1} for Mulato. The ventilation effect on chilli drying kinetics parameters was qualitatively assessed. As expected, the ventilation effect improved the drying rate and reduced the drying time, and consequently the cost of the drying process was reduced. In addition, a new method is presented to evaluate the cost of the drying process considering the kinetic parameters obtained. This new method allows evaluating the cost of the drying process in a simple way and with little experimental work. Consequently, it is possible to greatly reduce the cost of the drying process.

Keywords: drying kinetics; diffusivity; *Capsicum annum*; ventilation effect

Chilli (*Capsicum annuum*) is one of the most commonly consumed vegetables in Mexico (Galindo 2007). It is consumed both as fresh and as a dried product. Particularly, the drying process can prolong the preservation of chillies. The study of chilli drying process, due to its complexity, still attracts the attention of researchers around the world. Chilli drying can be used as an effective method due to its significant reduction in weight and volume that contributes to reduce the cost of production (Turk-Togrul & Pehlivan 2004). The cost of dried

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product depends on the drying process. Therefore, it is necessary to dry the product with minimum energy and time (Bakal et al. 2010). Several factors can influence chilli drying, for example velocity and air temperature, water diffusion, load density, thickness and shape of the product to be dried. However, scientific studies still continue analysing all the varieties of chillies and drying techniques (Barrientos-Sotelo et al. 2015). Dryers are developed to reduce the drying time and improve the quality of chillies.

Cortés-Rodríguez et al. (2013) investigated the drying characteristics of chilli using a continuous fluidised bed dryer. Reis et al. (2013) studied the effect of drying temperature on the nutritional and antioxidant qualities of cumari peppers. Balbay et al. (2013) presented a study about the drying kinetics of pistachio kernels. Hudakorn & Katejanekarn (2019) studied a solar dryer with a square-corrugated air collector with attached internal fins for red chilli drying. Villalpando-Guzmán et al. (2011) performed an experimental study on mango slices using a complementary microwave system. Aissa et al. (2014) evaluated the performance of a solar drier for sponge-cotton.

Béttega et al. (2014) studied the drying process of carrot and tomato slices using a vacuum microwave dryer. Kaewkiew et al. (2012) studied the performance of a large-scale solar dryer greenhouse for chilli drying. Also, the heat pump (Milić 2016) and fluid bed (Yamankaradeniz et al. 2016) were used to realise the drying process. Some research on the chilli drying technique has been addressed in the literature.

Lechtanska et al. (2015) investigated the effect of combined convective, microwave and infrared drying of green chilli. Their experiments proved that convective drying assisted with both microwave and/or infrared radiation significantly shortened the drying time. Vega et al. (2007) studied the effects of process temperatures between 50 and 90 °C on physicochemical properties, rehydration, colour, texture, vitamin C, antioxidant capacity and total phenolics during the drying of red chilli. Pal et al. (2008) proposed thin-layer drying experiments under controlled conditions for green sweet chilli in a heat pump dryer at 30, 35 and 40 °C and hot air dryer at 45 °C with relative humidity ranging from 19 to 55%. Veras et al. (2012) evaluated the effect of the drying process on vitamin C levels and physical properties of dedo-de-moca chilli. Convective drying was compared with freeze-drying in terms of product quality, structural properties, vitamin C retention and rehydration characteristics. Ghodbanan et al. (2017) used a non-linear programming optimisation method to optimise total steam and air consumption in the dryer section of multi-cylinder fluting paper machine, achieving a reduction of 11% in the total steam use. Also, several mathematical models may be used to describe the drying process and help in its optimisation, and assist in the effective design of dryers (Kiranoudis et al. 1993). Most of these models derive from the diffusion model of Fick's equation.

This aims at determining the effective diffusivity coefficient, which is related to the drying conditions (Tzempelikos et al. 2014). Particularly, the thin-layer drying models, describing the drying process, can be divided into three main categories, namely the theoretical, semi-theoretical and fully empirical ones.

The major difference between these groups is that the theoretical models suggest that the moisture transport is controlled mainly by internal resistance mechanisms, while the other two consider only external resistance. The semi-theoretical models can be obtained using the general solution of Fick's law. Also, using statistical relations, it is possible to find empirical models with a direct correlation between the moisture content and the time. The empirical and semi-empirical models are adequate at specific temperature intervals, air velocity and humidity for which they are applied (Babalis et al. 2006; Saeed 2010).

Mathematical modelling can contribute to the design of the dryer equipment regarding optimum drying times as well as better understanding of the drying mechanism (Sacilik 2007). Some semi-theoretical and empirical models frequently used to model the drying kinetics include Newton, Page, Henderson-Pabis, Overhults, Thompson and other models (Babalis et al. 2006; Bagheri et al. 2013). Corzo et al. (2008) analysed the Weibull distribution. This distribution can describe the moisture content of coroba slices, water losses and considers a complete factorial design for three levels of air temperature and speed. Marabi et al. (2003) proposed the Weibull distribution for the modelling of rehydration process. Bai et al. (2013) showed that the Weibull distribution model could well describe the drying curves for the moisture ratio vs. drying time, the profile of the model showed a high correlation coefficient and a low root mean squared error.

Zeng et al. (2015) investigated the effect of drying conditions on the parameters of Weibull distribution and its application in drying technology. The results showed that the Weibull distribution function was good in simulating the process of drying of kiwi fruit slices through microwave vacuum.

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In the literature, the drying of fruits has been widely reported, but the information is scarce in relation to the drying kinetics of vegetables, particularly of chilli. Therefore, the aim of this research was to reduce the cost of the drying process by optimising its kinetic parameters. The contribution of this paper is a new analysis of two types of chilli (Puya and Mulato) at different temperatures and two ventilation states (on/off); study of the drying behaviour using Weibull distribution and Newton's models; estimation of the Arrhenius activation energy during chilli drying. Both models were used because they use simplified equations and generate values very close to physical phenomena. Additionally, a new method is presented to easily determine the drying cost.

Additionally, two important contributions emerge from this study. (1) Through the analysis of the chilli drying using a small fan, responsible for the agitation of the drying chamber, it is possible to extrapolate these results to industrial drying cellars which need to optimise their financial resources. (2) Using the new proposed methodology, it is possible to accurately quantify the drying time, which allows optimising the energy needed to dry large quantities of chilli. Both contributions can be applied from various approaches, with the purpose of being used in different fields of engineering.

MATERIAL AND METHODS

The convective dryer. This study was performed on a convective dryer in order to evaluate separately the effects of temperature, mass flow rate and ventilation effect present within the drying chamber, which has a height of 40 cm. The specific characteristics of this device were previously reported (Guzmán-Valdivia et al. 2016), and the temperature uniformity was also characterised (Carrera-Escobedo et al. 2019). Additionally, this device is able to control the intake air speed and temperature, monitor the relative humidity at the inlet and outlet of the dryer and record the weight variation of the sample over time. The dryer is provided with a 2.4 Watt fan inside the drying chamber; with the option of increases in the ventilation rate and the coefficients of heat transfer and convection mass. During the experiments, a hot wire anemometer (portable; Amprobe, Germany) was introduced into the drying chamber, next to the samples to be dried.

The anemometer recorded a velocity of 0 m s^{-1} when the internal fan was off (low ventilation effect) and an average velocity of 0.046 m s^{-1} when the internal fan was on. Another anemometer showed no variation of the velocity at the inlet of the dryer, which means that the mass flow rate was kept constant while the velocity around the chilli samples changed.

We followed the methods of Carrera-Escobedo et al. (2019), and the electronic system consisted of an air flow sensor, which was a hot wire anemometer Amprobe model TMA20HW (Amprobe, Germany). Also, this system can measure the current flowing over the electric resistance heater (Allegro model ACS712 sensor; Allegro MicroSystems, USA).

The electronic system has two acquisition cards (National Instruments USB 6009 and MCC USB-TEMP TC Series) for analogue/digital data conversion, an electric resistance heater, two fans, humidity sensor and a load cell. The system has one s-beam load cell FUTEK model LSB300 to measure the weight of the chillies. More electronic characteristics of this system can be consulted in Guzmán-Valdivia et al. (2016). The homemade electronic system is presented in Figure 1. Two different types of chillies, Puya and Mulato, were used in this study. Eight batches of chillies were prepared for the study. The chillies were kept in a cool room at 3 °C for 24 h before drying. The chilli samples were dried using the convective dryer (240 V; Amprobe, Germany). The air was circulated by a constant speed blower (adjustable; Amprobe, Germany) and heated by electrical resistance. Two drying temperatures of 65 °C and 75 °C were used at 4.8×10^{-3} kg s^{-1} air mass flow rate with and without ventilation.

Figure 1. Convective dryer for the study of the drying process of chilli

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Drying kinetic equations. The thin-layer drying models, describing the drying process, can be distinguished in three main categories: theoretical, semi-theoretical and empirical ones. The main difference between these groups is that the theoretical models suggest that the transportation of moisture is controlled mainly by an internal resistance mechanism, while the other two consider only external resistance. Newton's model and Weibull distribution were proposed in the data fit analysis of this study. Both models are widely used, and their mathematical equations are very simple to solve. These models were used to investigate the ventilation effect in chilli drying. The exponential model is known as Newton's model and it is represented as Equation 1:

$$MR_{\mathrm{N}} = exp\left(-k_{\mathrm{N}}t\right) \tag{1}$$

where: MR_{N} – the simulated moisture ratio of Newton's model; k_{N} – the drying constant; t – the drying time (min).

The Weibull distribution can be described as follows (Equation 2):

$$MR_{\mathrm{w}} = a - b\left[exp\left(-k_{\mathrm{w}}t^{\mathrm{n}}\right)\right] \tag{2}$$

where: MR_{w} – the simulated moisture ratio of theWeibull distribution; k_{w} – Weibull distribution model constant; n – drying constant; a, b – drying coefficients; t – the drying time (min).

The dehydration process can be modelled by a simplified drying model to quantify the drying kinetics of plant species. A common model is the Lewis equation and has a general form (Equation 3):

$$MR_{\mathrm{EXP}} = \frac{X_{\mathrm{t}} - X_{\mathrm{e}}}{X_0 - X_{\mathrm{e}}} \tag{3}$$

where: MR_{EXP} – the experimental moisture ratio; X_{t} – the moisture content at any time t during drying (min); X_0 – the initial moisture content; X_{e} – the equilibrium material moisture content.

The slope method was used to estimate the effective diffusivity under different drying conditions. Analytical solution of Fick's equation was used, assuming that the transport of moisture occurs by diffusion, and the sample shrinkage is neglected. The diffusion coefficient and temperature have constant values; the effective diffusivity can be determined as follows (Equation 4):

$$MR_{\mathrm{eff}} = \frac{8}{\pi^2}\left[exp\left(-\frac{D_{\mathrm{eff}}\pi^2 t}{4L^2}\right)\right] \tag{4}$$

where: MR_{eff} – the effective moisture ratio; D_{eff} – the effective diffusion coefficient ($\mathrm{m^2\ s^{-1}}$); L – the half thickness of the samples (m); t – the drying time (min).

The dependence of drying constants for Newton's and Weibull models was evaluated using the Arrhenius type equation as given below (Equation 5):

$$D_{\mathrm{eff}} = D_0\left[exp\left(-\frac{E_{\mathrm{a}}}{R_{\mathrm{g}}T}\right)\right] \tag{5}$$

where: D_{eff} – the effective diffusion coefficient ($\mathrm{m^2\ s^{-1}}$); E_{a} – the activation energy ($\mathrm{kJ\ mol^{-1}}$); D_0 – the pe-exponential factor of the Arrhenius equation ($\mathrm{m^2\ s^{-1}}$), R_{g} – the constant of universal gas ($\mathrm{J\ mol^{-1}\ K^{-1}}$); T – the temperature (°C).

The above exponential form of Arrhenius equation can be expressed as follows (Equation 6):

$$lnD_{\mathrm{eff}} = lnD_0\left[exp\left(-\frac{E_{\mathrm{a}}}{R_{\mathrm{g}}T}\right)\right] \tag{6}$$

A plot of InD_{eff} versus $1/T$ gives a straight line of $E_{\mathrm{a}}/R_{\mathrm{g}}$ slope and consequently the activation energy (E_a).

Statistical analysis. The drying curves were analysed using non-linear regression techniques. Newton's model and Weibull distribution were fitted using Minitab® 17 software. This software can solve non-linear regressions using the Levenberg-Marquardt method, a nonlinear algorithm widely used in the least squares fitting. This method combines the steepest descent and Taylor series-based approach to obtain a fast, reliable technique for non-linear optimisation. The statistical analysis of experimental data was determined using an analysis of variance (ANOVA) to estimate any statistically significant difference.

The best fitting equation was selected based on the correlation coefficient R^2 and the reduced sum of squared errors (SSE). The lowest SSE, along with the highest (near to 1) R^2 value was used as the criteria to evaluate the fit quality of the proposed model (Equations 7 and 8).

$$SSE = \frac{1}{N}\sum_{j=1}^{N}\left(MR_{\mathrm{ei}} - MR_{\mathrm{ci}}\right)^2 \tag{7}$$

$$R^2 = \frac{\sum_{j=1}^{N}\left(MR_{\mathrm{ci}} - \underline{MR_{\mathrm{ei}}}\right)^2}{\sum_{j=1}^{N}\left(MR_{\mathrm{ei}} - \underline{MR_{\mathrm{ei}}}\right)^2} \tag{8}$$

where: N – the number of data values; j – the number of terms; MR_{ei} – the experimental moisture ratio; MR_{ci} – the calculated moisture ratio; $\underline{MR_{\mathrm{ei}}}$ – the average experimental moisture ratio.

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Table 1. Uncertainty parameters of the equipment used

Equipment	Measurement variable	Accuracy
Anemometer	air flow	0.1%
Humidity sensor	humidity	± 2.0% RH
Temperature sensor	temperature	STH15: ± 0.3% thermocouples: ± 0.345%
Load cell	weight	0.05%

RH – Relative humidity; STH15 – SparkFun humidity and temperature sensor breakout (SparkFun Electronics, USA)

The uncertainty values of the equipment used are presented in Table 1, and are in the same order as the experimental values.

Drying experiments. The chillies were dried, without cutting them. This was due to regional customs. The height of Puya chilli is 3 cm, and Mulato is 5 cm in height. The chosen experimental drying conditions are presented in Table 2.

The drying rate is proportional to the moisture content, and it was calculated using Equation 9 (Toledo 2007):

$$-\frac{dW}{dt} = \mathrm{k}W \tag{9}$$

where: W – the moisture content (g water / g dry matter); k – a constant (1 m^{-1}).

One way to approximate the value of the drying rate of the above equation is to make a difference between two humidity values during a determinate time interval.

Proposed method to determine the drying cost. Our research group proposes a new easy method to obtain the drying cost in a simple way.

The procedure to obtain the drying cost is described step by step in Figure 2.

Equation 4 was used to obtain the 3.3924 × 10^{-6} m^2 value. Then, the variable t was isolated (Equation 10):

$$t = -\frac{4L^2}{D_{\mathrm{eff}}\pi^2}\left[ln\left(-\frac{MR_{\mathrm{eff}}\pi^2}{8}\right)\right] \tag{10}$$

where: t – the drying time (min); L – the half thickness of the samples (m); D_{eff} – the effective diffusion coefficient (m^2 s^{-1}); MR_{eff} – the effective moisture ratio.

The half thickness (L) of the chilli sample is 0.002 m; MR_{eff} has a value of 0.1, because it is a value in which the food is well preserved; the D_{eff} value takes a different value depending on the temperature.

Simplifying Equation 10, it is possible to show how to get the previous value (Equation 11):

$$t = -\frac{0.8981\,(0.002)^2}{D_{\mathrm{eff}}} = \frac{3.3924\times 10^{-6}\,\mathrm{m}^2}{D_{\mathrm{eff}}} \tag{11}$$

where: t – the drying time (min); D_{eff} – the effective diffusion coefficient (m^2 s^{-1}).

In order to clarify the algorithm, an example with the values used in this study is shown in Figure 3. The temperature value of 323 °C is used as an example. This value was added to show that it is possible to calculate the cost of drying at high temperatures.

Table 2. Drying conditions

Type of chilli	Initial moisture dry basis (g water kg^{-1})	Initial moisture wet basis (–)	Air temperature (°C)	Experiment	Ventilation (Y/N)
Puya	3.51	0.7783	65	1	Y
				2	N
			75	3	Y
				4	N
Mulato	6.102	0.8591	65	5	Y
				6	N
			75	7	Y
				8	N

Y – yes; N – no

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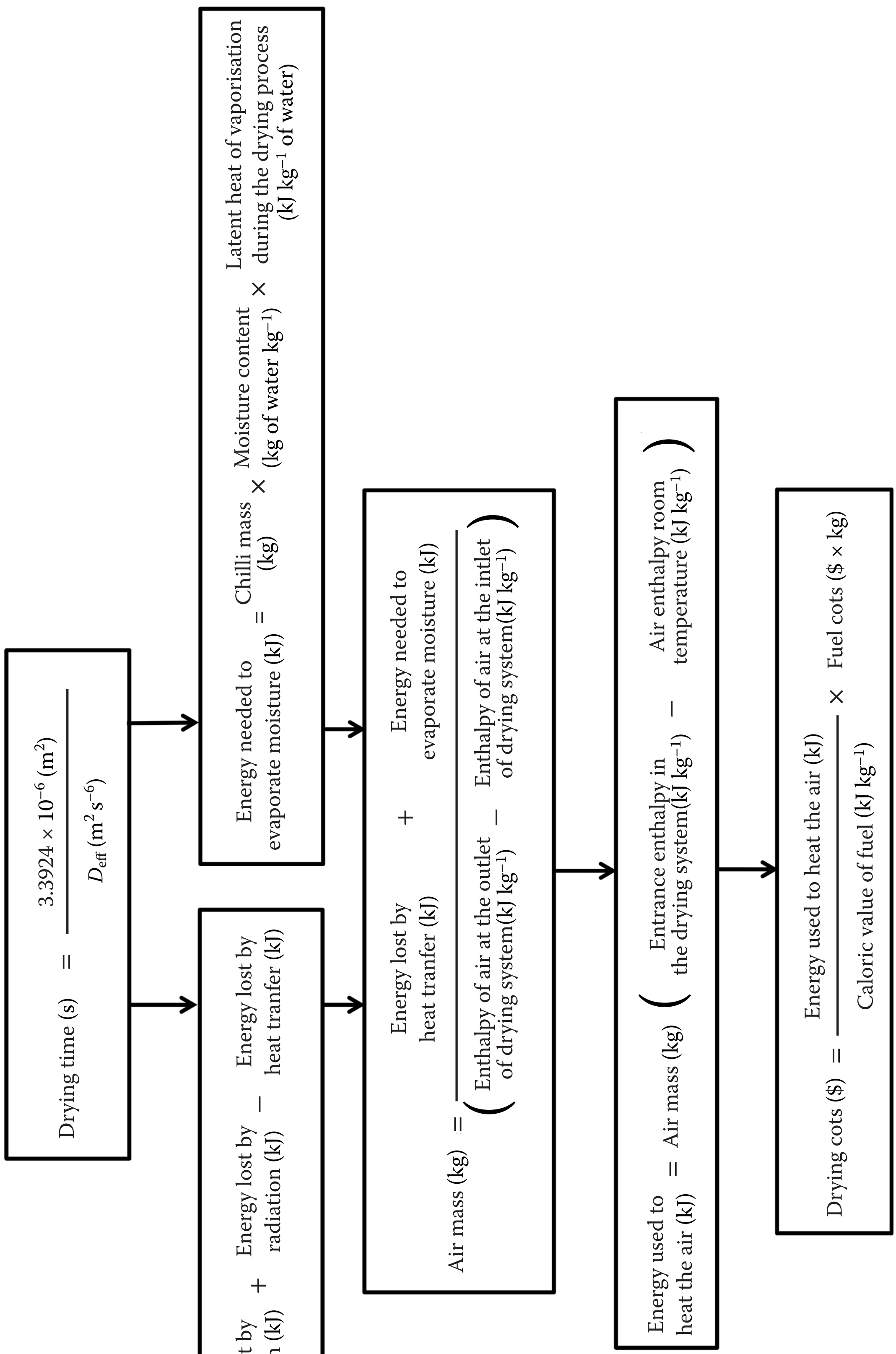

Figure 2. Proposed method to determine the drying cost
D_{eff} – the effective diffusion coefficient ($m^2 s^{-1}$)

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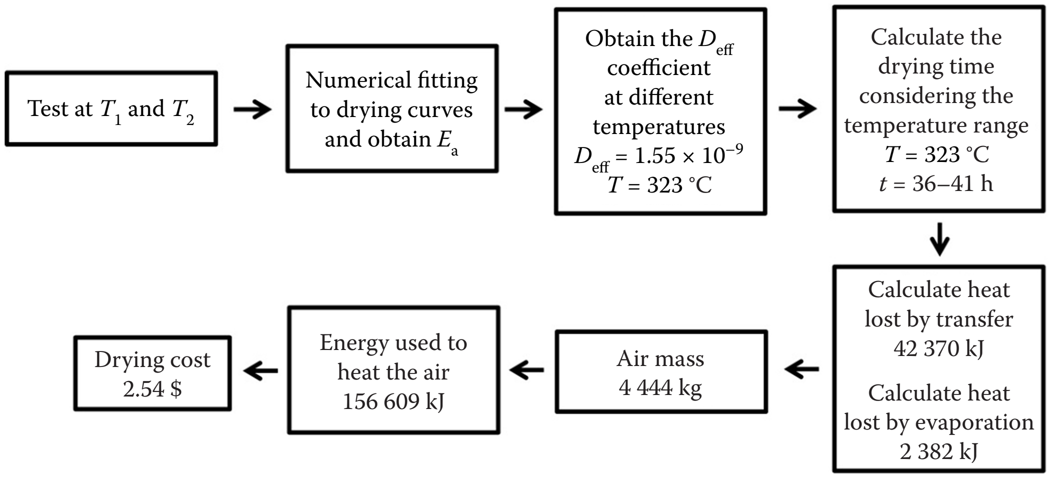

Figure 3. Example with the values used in the drying of Mexican chillies

E_a – the activation energy (kJ mol^{-1}); D_{eff} – the effective diffusion coefficient (m^2 s^{-1}); T – temperature (°C); t – the drying time (min).

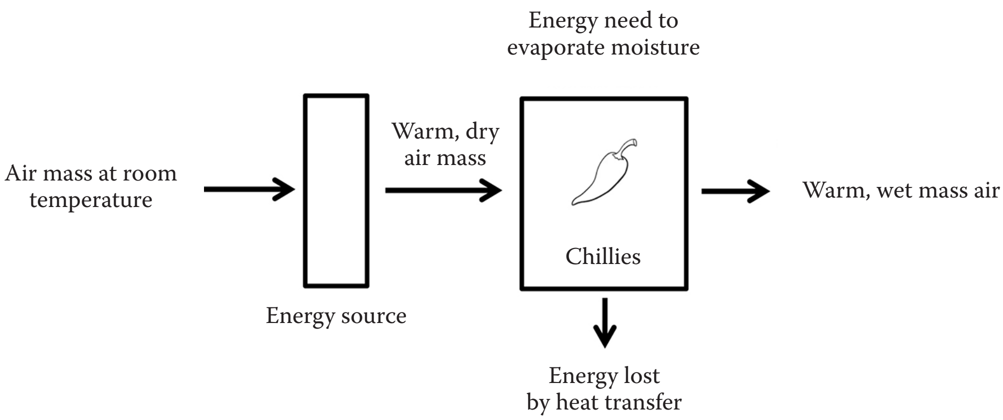

Figure 4. Schematic diagram of the drying process of Mexican chillies

Finally, a schematic diagram of the drying process of Mexican chillies is presented in Figure 4.

RESULTS AND DISCUSSION

Drying curves. Figure 5A presents the experimental drying curves of moisture content versus drying time with and without ventilation for drying of Puya chilli at 65 °C. Figure 5B presents the same information but at 75 °C. All curves of chilli drying showed a clear exponential behaviour. Also, it was observed that the drying time decreased with ventilation. It is evident that the drying rate was increased when the ventilation level was high. The value of the moisture ratio decreases rapidly, with a consequent increase of the drying rate, when ventilation is present. For example, the time required to achieve moisture content lower than 0.2 with ventilation at 65 °C for Puya chilli was 900 min. On the other hand, the time required to achieve moisture content lower than 0.2 without ventilation at 65 °C for Puya chilli was more than 1 200 min.

A similar trend of decreasing drying time for Mulato chilli was also observed. Figure 6A presents the experimental drying curves of moisture content versus drying time with and without ventilation for drying of Mulato chilli at 65 °C. Figure 6B presents the experimental drying curves of moisture content versus drying time with and without ventilation for drying of Mulato chilli at 75 °C.

It is observed that the drying curves for both types of chillies are similar. After an initial short period which practically matches with the heating up peri-

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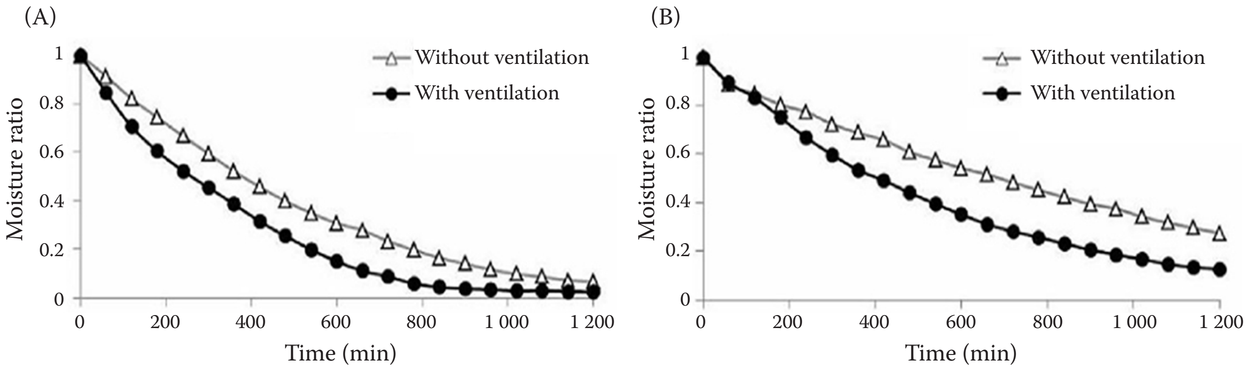

Figure 5. Experimental drying curves of Puya chilli at 65 °C (A) and 75 °C (B)

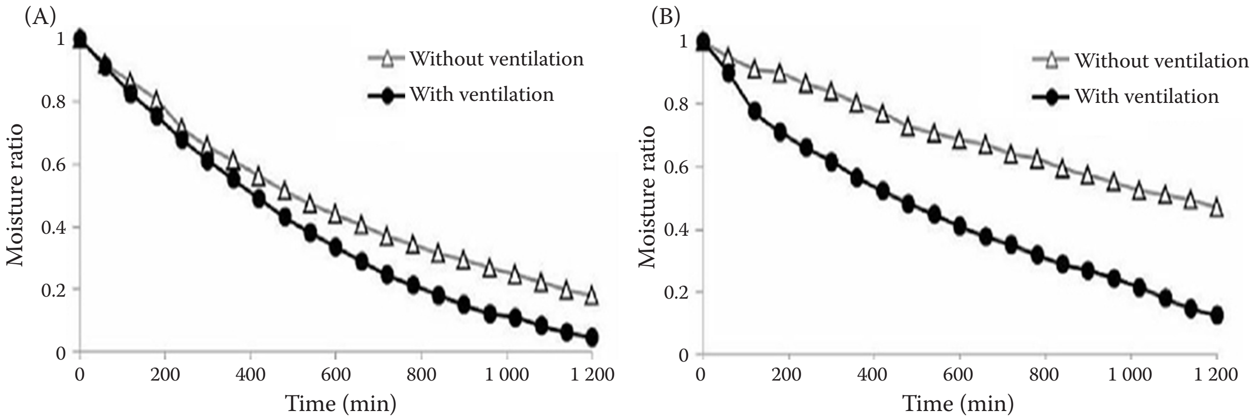

Figure 6. Experimental drying curves of Mulato chilli at 65 °C (A) and 75 °C (B)

od, the drying rate reaches a maximum value. This behaviour can be ascribed to the ventilation effect during the drying process which improves the drying rate and decreases the drying time. These experimental results show another important fact: the chilli drying can be improved when ventilation is included during the drying process.

Modelling of chilli drying. Newton's and Weibull distribution models were fitted to the experimental results with ventilation, using the Levenberg-Marquardt method of non-linear regression procedure. Table 3 shows the constants and coefficients for Newton's and Weibull distribution models. For Puya chilli, it is observed that the drying constant in Newton's equation (k_N) increased when the drying temperature was increased. On the other hand, the Weibull constant (k_w) decreased when the drying temperature was increased. Similar results were found for Mulato chilli. It was also observed that k_N increased with ventilation. Figure 7 shows the comparison of experimental and calculated moisture ratio of Puya chilli at 65 °C (A) and 75 °C (B). Figure 8 shows the comparison of experimental and calculated moisture ratio of Mulato chilli at 65 °C (A) and 75 °C (B).

It is evident that the fitting performance follows the general rule of the regression analysis: the more coefficients introduced, the more accurate predictions are obtained. It can be concluded that the Weibull distribution demonstrates to be a better fit than Newton's model. In addition, the numerical fit was adequate for experimental moisture data.

Statistical analysis of models. Two statistical test methods were used to select the best model describing the drying curves, the correlation coefficient R^2 and the reduced sum of square errors (SSE). Table 4 shows the results of the statistical tests, including a comparison between Newton's model and the Weibull distribution. These statistical tests have been used by other

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Table 3. Constants and coefficients for Newton's and Weibull models

Type of chilli	Temp. (°C)	Newton's model	Weibull model			
		k_N	a	b	k_w	n
Puya	65	0.001	–0.341	–1.328	0.002	0.881
		0.001	–0.720	–1.715	0.0008	0.923
	75	0.002	0.0003	–0.984	0.0008	1.175
		0.001	–0.220	–1.1995	0.0006	1.083
Mulato	65	0.001	–0.278	–1.2938	0.001	0.936
		0.0006	0.178	–0.8172	0.0004	1.093
	75	0.002	–0.018	–1.0154	0.0004	1.226
		0.001	–0.148	–1.1470	0.003	0.842

k_N – Newton's model constant; a, b, k_w and n – empirical constants of Weibull model

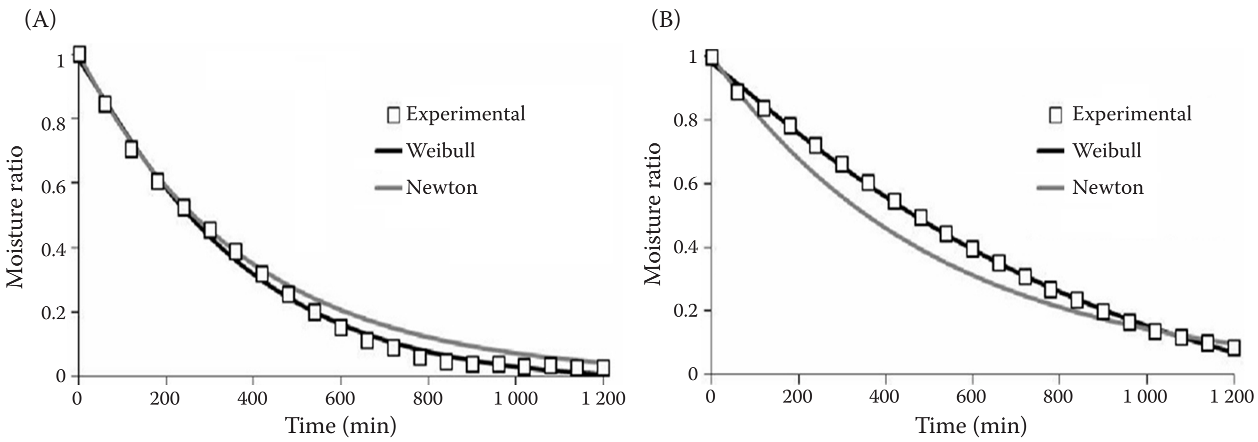

Figure 7. Comparison of the experimental and calculated moisture ratio of Puya chilli at 65 °C (A) and 75 °C (B)

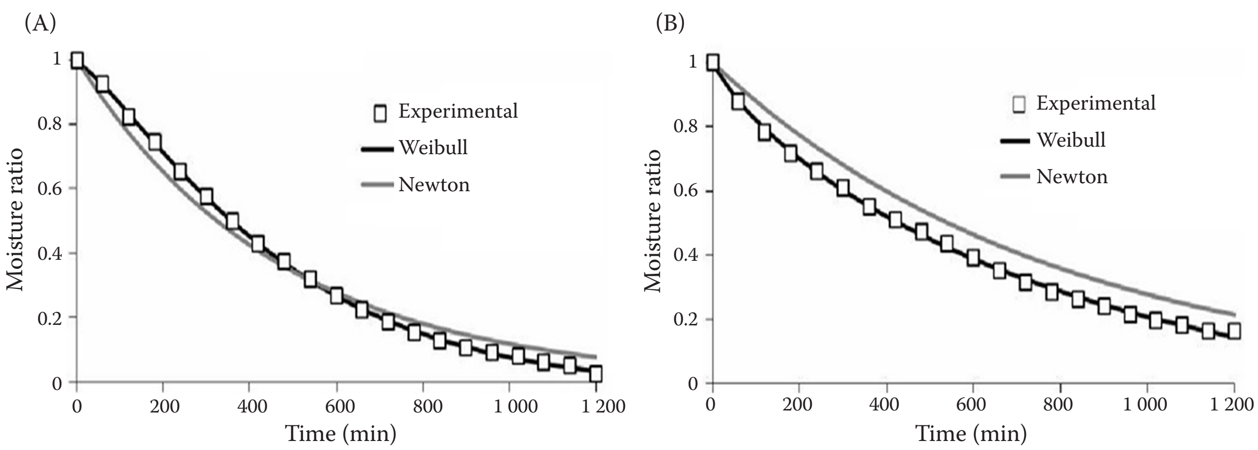

Figure 8. Comparison of the experimental and calculated moisture ratio of Mulato chilli at 65 °C (A) and 75 °C (B)

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Table 4. Coefficient values

Type of chilli	Air temperature (°C)	Newton's model		Weibull distribution
		SSE	R^2	SSE
Puya	65	0.016	0.989	0.012
	75	0.011	0.993	0.009
Mulato	65	0.021	0.982	0.008
	75	0.059	0.969	0.030

SSE – sum of squared errors; R^2 – coefficient of determination

researchers to analyse experimental data acquired in the study of chilli drying. As it can be seen, the R^2 and SSE values range from 0.969 to 0.995 and from 0.059 to 0.008, respectively.

According to these results, the model that best fitted the experimental data, considering the determination coefficient (R^2 > 0.99) as the first criterion, was the Weibull distribution.

Effective diffusivity and activation energy. The most widely used theoretical model in drying of individual particles of food products is the diffusive model which places all the complexity of the problem on an effective transport coefficient. From the results of the ANOVA carried out on the diffusivity coefficients using Minitab® 17 software with a confidence level of 95% and $P < 0.05$, it was established that there is a statistical difference between the diffusivities at all the tested conditions. The effect of temperature on the moisture diffusion coefficient can be described by an Arrhenius-type equation.

The activation energy was determined by plotting the natural logarithm of D_{eff} versus the reciprocal of drying temperature ($1/T$). The slope of the straight line equals the quotient E_a/R_gT. Table 5 shows the effective diffusivity and activation energy.

The effective diffusivity values were calculated from 6.82×10^{-10} to $1.13 \times 10^{-9} m^2 s^{-1}$ for Puya and 2.55 to $3.26 \times 10^{-9} m^2 s^{-1}$ for Mulato. The obtained activation energy values were 49.7 kJ mol^{-1} for Puya and 24.1 kJ mol^{-1} for Mulato. The experimental data was compared with similar data found in the literature and the results are considered satisfactory. These results of activation energy agreed with those obtained by other researchers: 23.35 kJ mol^{-1} and 28.4 kJ mol^{-1} for Red chilli (Turhan et al. 1997; Di-Scala & Crapiste 2008) and 39.7 kJ mol^{-1} for Lamuyo chilli (Vega et al. 2007). From the simulation and experimental results of the study it can be concluded that the application of these results can be useful in the field of agriculture and food sciences to estimate optimum drying conditions needed to achieve a final water content of different types of chilli required for further processing.

Table 5. Effective diffusivity and activation energy

Type of chilli	Air temperature (°C)	Effective diffusivity (m^2 s^{-1})	Activation energy (kJ mol^{-1})
Puya	65	6.82×10^{-10}	49.7
	75	1.13×10^{-9}	
Mulato	65	2.55×10^{-9}	24.1
	75	3.26×10^{-9}	

Drying cost analysis. Figure 9 shows the energy used to (a) evaporate the moisture from the Puya chillies, (b) keep the drying chamber warm and (c) cost of the drying process and (d) drying time.

Figure 9A shows how the energy needed to evaporate the moisture decreases as the temperature rises. The impact of this phenomenon would be a decrease in the cost of the drying process if this were the only involved parameter.

Figure 9B shows that, as the drying temperature rises, the energy lost by heat transfer decreases. Although this might be unexpected, the energy loss becomes smaller because the drying time also decreases, as shown in Figure 9D. So far, the energy needed to accomplish the drying has diminished as the drying temperature has risen. So, the cost should also decrease, but it does not.

As shown in Figure 9C, the cost has a maximum value at 55 °C for the line calculated with no ventilation. If there is ventilation, the cost always increases with the drying temperature and tends to a maximum value of 90 Mexican pesos (approximately 3.85 dollars).

The cost is always higher if no ventilation is added. The reason why the cost does not decrease as the drying temperature increases is because more energy is required to increase the drying air temperature.

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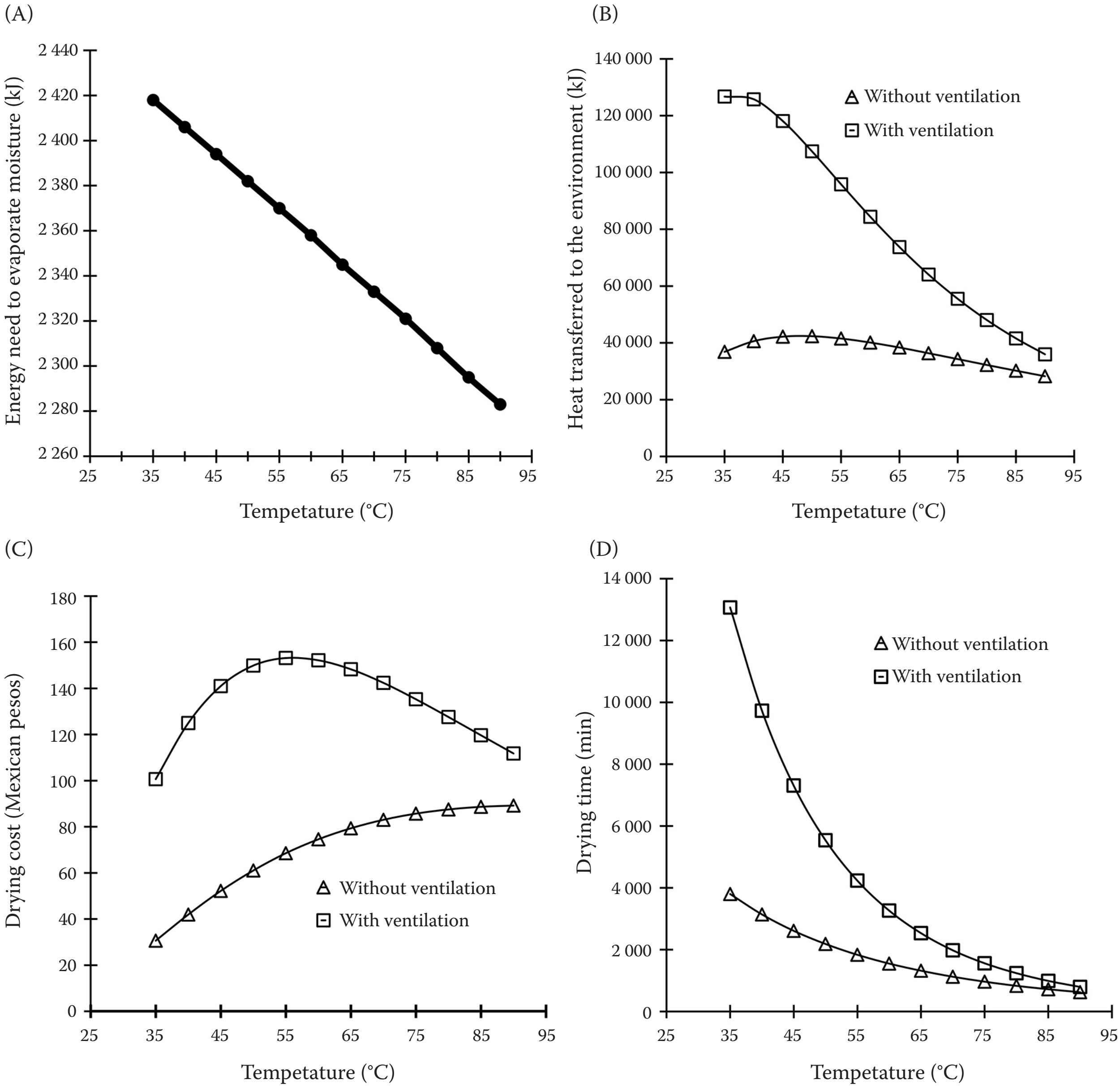

Figure 9. Energy used to evaporate the moisture from the Puya chillies (A), keep the drying chamber warm (B), cost of the drying process (C) and drying time (D)

CONCLUSION

A new algorithm was presented to easily determine the drying cost for different types of chillies at different drying conditions. A clear cost reduction can be achieved by using the new method proposed. The reason why the cost does not decrease as the drying temperature increases is because more energy is required to increase the drying air temperature. The ventilation effect on chilli drying was studied. The moisture content and drying time in both types of chilli decreased with the increase of ventilation. Two mathematical thin-layer drying models, available in the literature, were fitted to experimental data obtained when two types of chilli were dried at 65 and 75 °C, with and without ventilation and with an air velocity of 0.5 m s^{-1}. The Weibull distribution demonstrates a better fit than Newton's model. Relations between the Weibull distribution and Newton's model parameters and the drying conditions for the calculation of the moisture ratio in relation to drying time were determined and reported. The drying kinetic pa-

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rameter k_N increases as the temperature or ventilation grows while the drying kinetic parameter k_W increases with ventilation and decreases with temperature. The moisture diffusivity coefficients of chillies were in the range of 6.82×10^{-10} to 1.13×10^{-9} m^2 s^{-1} for Puya and 2.55 to 3.26×10^{-9}m^{2}s^{-1} for Mulato. The effect of temperature on the diffusivity was described by the Arrhenius equation with activation energy of 49.7 kJ mol^{-1} for Puya and 24.1 kJ mol^{-1} for Mulato. Finally, the optimisation of kinetic parameters has reduced costs of the drying process.

The next study will undertake the addition of a recirculation system and energy analysis for the chilli drying process. These findings will be useful for further studies of chilli drying.

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