EXPERIMENTAL INVESTIGATION AND MATHEMATICAL MODELING OF HOT AIR CONVECTIVE DRYING OF TOMATO PASTE UNDER NEAR SOLAR DRYING OPERATING CONDITIONS

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Abstract.- *The present study was carried out to stabilize, by drying means, the surplus of local tomato production. Obtaining an organic product in the form of tomato paste was then invested during the study. The effect of two different drying conditions (air temperature and air velocity) on the drying behavior of a thin-layer tomato paste was experimentally investigated. Experimental drying kinetics were obtained at 45, 50, and 60°C performed with airflow velocities of 1.5 and 2.5m/s. Results showed that increasing of air-drying temperature from 45 °C to 60 °C reduced drying time by 48.66% and 44.7% for both air velocities, respectively. Among nine fitted mathematical models, Demir et al model was found the best model to describe thin-layer drying of tomato paste under different conditions. The effective moisture diffusivity values have been estimated from Fick's diffusion model pointing out that it has been increased with the increase of the drying air temperature. Finally, the activation energies were found to be 44.836 and 38.159 Kj/mol for air velocities 1.5 and 2.5 m/s respectively.*

Key words: Hot air convective drying**,** tomato paste, mathematical modeling, moisture diffusivity, activation energy

ETUDE EXPÉRIMENTALE ET MODELISATION MATHEMATIQUE DU SÉCHAGE CONVECTIF À AIR CHAUD DE LA PÂTE DE TOMATE SOUS CONDITIONS OPÉRATOIRES PROCHES DU SÉCHAGE SOLAIRE

Résumé.- *La présente étude a été realisée dans le but de stabiliser, par séchage, le surplus de la production locale des tomates. L'obtention d'un produit biologique sous forme de pâte de tomate a ensuite été investie lors de l'étude. L'effet de deux conditions de séchage (température et vitesse de l'air de séchage) sur le comportement de séchage de la pâte de tomate en couche mince a été expérimentalement étudié. Les cinétiques de séchage ont été obtenues à 45, 50 et 60 °C avec des vitesses d'écoulement d'air de 1.5 et 2.5 m/s. Les résultats obtenus ont montrés que l'augmentation de la température de séchage de 45 à 60 °C a réduit le temps de séchage par 48.7 % et 44.7 % pour les deux valeurs de vitesse 1.5 et 2.5 m/s respectivement. Parmi les neuf modèles mathématiques ajustés, le modèle Demir et al. s'est avéré le meilleur pour décrire le séchage en couche mince de la pâte de tomate dans les différentes conditions opératoires. Les valeurs effectives de la diffusivité ont été estimées à partir du modèle de diffusion de Fick, soulignant qu'elle a observé une augmentation en même sens que l'augmentation de la température de l'air de séchage. Enfin, l'énergie d'activation a été estimée à 44.83 et 38.16 kJ/mol pour les vitesses d'air de 1.5 et 2.5 m/s respectivement.*

Mots-clés: *Séchage par convection à air chaud, pâte de tomate, modèle mathématique, diffusivité, énergie d'activation*

Introduction

Drying of foods is a very important method for the food industry and offers possibilities for novel products to consumers [1].

Drying is an alternative method for long storage and an ancient process used to preserve food and extend the shelf life of food [2]. Large quantities of food products are dried to improve shelf-life, reduce packaging cost, lower shipping weights, enhance appearance, encapsulate original flavor, and maintain nutritional value [3]. It also reduces the mass and volume of the products resulting in minimum transportation costs. There are many techniques for long storage of food products [4]. Among the drying techniques, hot air drying is largely employed to dry foodstuff [5].

Tomatoes (*Lycopersicon esculentum* L. va) are one of the most important grown vegetable crops, mostly in the world. The cultivation of tomato is widespread throughout the world. According to FAO (2014), the universal production of tomato in 2014 is170.750.767 million tons, whereas Algeria produced 1.065.609 million tons with a world rank of 18 and a world share of 0.6%. In particular, 90% of world output is produced in the northern hemisphere (Mediterranean area, California, and China) [6].

The industrial processing of tomato, which is considered a highly deformable material, leads to a great variety of derived products from which: concentrated tomato products, pizza sauce, tomato powder, peeled tomato, tomato sauce seasoned [7].

Tomato drying has been investigated to a great extent and a lot of data are available in the literature. [8] studied experimentally and theoretically the correlation between the constant K and the drying temperature of the product in a thin layer using indirect solar dryer operating with natural convection to dry tomato, onion, fig, and grape. SAHIN *et al.* (2011) investigated experimentally the effects of several drying methods, such as hot-air drying (at 65, 75, and 85 °C drying temperatures), sun drying, vacuum drying, and freeze-drying, and pretreatments, namely dipping into 1% ascorbic acid + 1% citric acid and dipping into 2% sodium metabisulphite after 2% ethyloleate + 4% potassium carbonate solution application on lycopene retention and color properties of dried tomato slices [9]. SAMIMI-AKHIJAHANI and ARABHOSSEINI (2018) examined the effect of a lab-scale PV-assisted solar drying system equipped with a sun tracking unit to study the drying behavior of tomato slices during the drying process [10]. The samples were tested at different air velocities (0.5-2 m/s) and product thicknesses (3-5 mm) with and without the application of a sun-tracking mechanism. KROKIDA *et al.* (2003) studied the drying kinetics of some vegetables including tomato fruit, and determined the equilibrium moisture content of each dried product. He found that temperature, which ranged between 65 and 85 °C for drying kinetics and 30 and 70 °C for desorption isotherms, was the most important factor affecting the experimental results [11]. BAGHERI *et al.* (2013) modeled the thin layer solar drying of tomatoes slices using a basic indirect solar dryer [12]. The drying experiments were carried out on tomato slices with a thickness of 3. 5 and 7 mm at the air velocity of 0.5 and 1 m/s. Page model was the most appropriate model for the drying experiment, with a high ability between drying conditions (thicknesses and air velocity). ISMAIL and AKYOL (2016) investigated experimentally and by modeling the effects of open sun drying and pretreatment on drying characteristics of cherry tomatoes. Pretreatment of cherry tomatoes caused a decrease in the drying time by 15% (26 – 22 h) [13]. VERMA *et al.* model was found the best mathematical model represented the open-air sun drying behavior of cherry tomatoes. The best color of samples was found for the pre-treated dried cherry tomatoes. SACILIK *et al.* (2006) [14] studied experimentally solar drying curves of tomato cut in half-dried under atmospheric conditions of Ankara (Turkey) and they compared them to the way drying in the open air. [15] Compared the drying time and the quality of dried tomatoes, using a greenhouse solar drying with and without a solar concave concentrator. Concentrating solar drying allowed reducing drying time by 21%. It was also shown that the use of concentrating solar drying did not affect negatively on tomatoes quality. The only hindrance is that the farmer has to move the concentrator every one hour each day for a more reflective surface. DOYMAZ (2007) [16] studied experimentally the effect of treatment on drying kinetics of tomatoes cut in half and distributed on shelves of a forced convection dryer at temperatures of 55, 60, 65, and 70 °C by using electrical resistors passing perpendicularly through the grids [16]. HAMDI and KOOLI (2018) [17] compared the drying characteristic of thin layer tomato dried in a mixed mode solar greenhouse dryer and under open sun. She observed that the dryer shows better performance than the open sun. Midilli-Kucuk model was the best model for both drying methods. BELGHITH *et al.* (2016) investigated the modeling effect of drying parameters on the drying behavior of tomato quarters and halves along with the exchange surface with the surrounding environment [18]. In order to describe the drying behavior of tomato slices, four drying models were fitted to the drying data. Among the models, Midilli-Kucuk model was found to be most suitable model for describing the drying curve of the thin layer drying process with coefficient of determination (R^2) and the reduced Chi square (χ^2) values ranged between 0.9891 and 0.99997 1.743 10^{-6} and 6.4 10^{-4} , respectively for tomato cut into halves, and between 0.94567 and 0.99998, 1.735 10^{-6} and 3.17 10^{-3}, respectively for tomato cut into quarters.

From that vast extensive literature review on the impact of changes in drying parameters during drying operation, very scarce information is available on the thin-layer drying behavior of tomato, particularly the tomato paste that is less investigated.

On the other hand, the available literature on the different drying techniques of tomatoes shows that the most suitable treatment temperatures are in the range of 40°C to 70°C which represents the order of magnitude commonly provided by solar drying. Nevertheless, in the case of solar drying, the process is constrained by the instability of the temperature throughout the day, which could affect the good prediction of the physical behavior and the quality of the final product.

On the other hand, the available literature on the different drying techniques of tomatoes shows that the most suitable treatment temperatures are in the range of 40°C to 70°C which represents the order of magnitude commonly provided by solar drying. Nevertheless, in the case of solar drying, the process is constrained by the instability of the temperature throughout the day, which could affect the good prediction of the physical behavior and the quality of the final product.

Hence, this study was carried out to fulfill the existing research gaps on thin layer modeling of tomato paste. The main objectives of this study are to:

- Investigated by modeling the drying kinetics of dried tomato paste using a controlled convective dryer working under near solar drying operating conditions.
- Predict the most suitable drying models for describing the drying behavior of tomato paste with various drying conditions.
- Study the effect of drying conditions on effective moisture diffusivities and activation

energy of tomato paste.

1.- Material and methods

2.1.- Sample Preparation

Fresh local tomatoes (*L. esculentum. var*) were bought at a local market in Ouargla, southern Algeria. They were singled out one by one using a visual criterion like color, size, absence of physical damage, and uniform maturation degree. Forty kilograms of tomatoes were properly washed with running water to remove skin, dirt and then cut into halves or quarters. After that, it was ground in a kitchen blender and separated in a whole series of sieves of different sizes to remove the skin and the seeds from the paste. Finally, the paste was drained in a tissue bag to obtain 4 kilograms of tomato paste, and 15 liters of tomato juice (fig. 1). The tomato paste was sealed in plastic bags and stored at 4°C.

Figure 1.- Samples preparation

1.2.- Initial Moisture Content Determination

The sample's initial moisture content was determined using a direct measurement method, which consists of placing a sample weight of 3g in a Laboratory Incubator at 105±1°C for 24 h until a constant weight is obtained.

1.3.- Experimental Procedure

Prior to starting the drying experiments, the system was run for at least a quarter of an hour (15 mn) to obtain steady-state conditions. A batch of 50 g of fresh tomato paste has been taken out from the refrigerator to rest. Samples were spread in a perforated tray (dimensions in cm: 5×5±0.1) in a thin layer of about 1.5 cm thickness.

The tray loaded with tomato paste was suspended to a digital balance with a standard error of±0.001 g. Air parameters were adjusted and controlled continuously using an industrial programmable controller. In order to guarantee dried product quality, experiments were performed in the temperature range from 45 to 60°C, in a relative humidity of 16 % at two air velocities of 1.5 and 2.5m/s. The mass of the product was continuously measured using an electronic balance (precision of 0.01g) and recorded by a microcomputer.

1.4.- Drying Equipment

Drying experiments were performed in a laboratory scale, convective, and vertical downward flow dryer (designed and constructed in the Laboratoire d'Energétique et des Transferts Thermiques et Massiques (LETTM) in French, Sciences Faculty of Tunis). This dryer is designed to work in a closed loop and was equipped with a programmable controlling system for drying air parameters. The layout of the dryer is given in (fig. 2).

1.5.- Drying Unit

The dryer is equipped with a controlling system for temperature, velocity, and relative humidity of drying air and consists of a vertical airflow conducted through a tunnel to cross perpendicularly the tomato paste samples spread uniformly on a perforated tray, placed inside the drying chamber. Moisture loss was obtained through periodic measuring the weight of the sample during drying which was recorded at 30 min intervals using a digital balance interfaced with a PC to ensure the data acquisition.

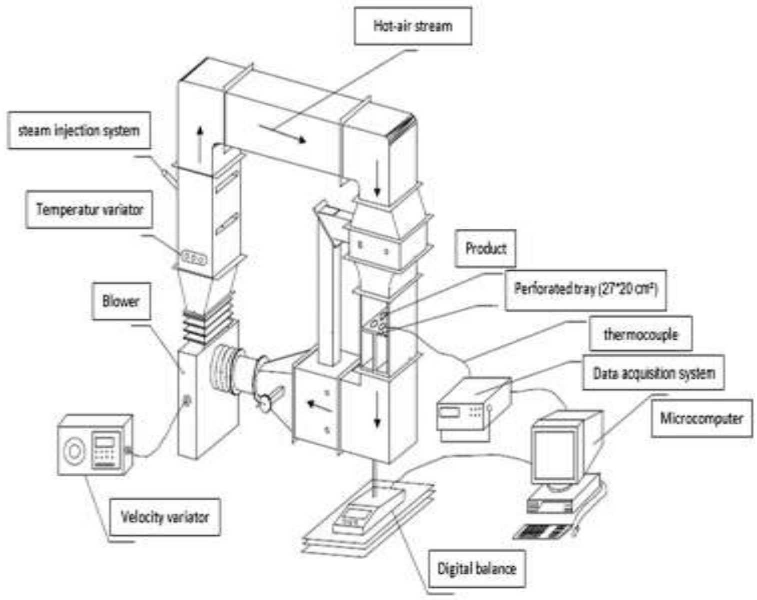


Figure 2.- Schematic diagram of the drying system

2.6.- Experimental Uncertainty

Based on instrument selection, drying condition, calibration, observation, test planning, certain errors and uncertainties occur during measurements [19]. During the drying experiment of tomato paste, the drying temperature, air velocity, relative humidity, and weight losses were measured with appropriate instruments. The uncertainties of measurements are presented in (tab. I).

Table I.- Uncertainties of the various parameters

Parameters	Expression	Unit	Value
Drying chamber temperature	T	°C	±1
Drying chamber relative humidity	RH	%	±2
Weight loss of the sample	m	G	±0.01
Air velocity	V	m/s	±0.1
Samples dimensions	l	Cm	±0.1

2.7.- Modeling of Thin Layer Drying Curves – Theoretical Approach

The drying curves were fitted to nine different moisture ratio models to select a suitable model for describing the drying process of tomato paste in (tab. II).

Table II.- Mathematical models for the drying curves

No	Model	Model equation	References
1	**Lewis**	$MR = exp(-kt)$	[20]
2	**Page**	$MR = exp(-kt^n)$	[21]
3	**Modified page**	$MR = \left[exp(-kt^n)\right]$	[22]
4	**Henderson and Pabis**	$MR = a.exp(-kt)$	[23]
5	**Logarithmic**	$MR = a\ exp(-kt) + c$	[24]
6	**Wangh and Singh**	$MR = 1 + at + bt^2$	[25]
7	**Diffusion approach**	$MR = aexp(-kt) + (1-a)exp(-kbt)$	[26]
8	**Demir et al.**	$MR = a.exp(-kt^n) + b$	[27]
9	**Midilli et al.**	$MR = a.exp(-kt^n) + bt$	[28]

The moisture ration of the samples during convective drying was expressed by the Equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

The values M_e are relatively small compared to M_t and M_0 where error implied in the simplification is negligible. Equation (1) becomes:

$$MR = \frac{M_t}{M_0} \tag{2}$$

2.8.- Statistical Analysis

To validate the goodness of the fit, three statistical criteria, namely root of mean square error (RMSE), reduced chi-square (χ^2), and coefficient of determination (R^2) were calculated using the Origin software program. The coefficient of determination (R^2) is one of the primary criteria in order to evaluate the fit quality of selected models. In addition to R^2, reduced chi-square (χ^2) and root mean square error (RMSE) are used to determine the suitability of the fit [29, 30]. For the best fit, the R^2 value should be high and RMSE values should be low. This can be calculated as follows:

$$RMSE = \left[\frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{\exp,i})}{N}\right] \tag{3}$$

$$x^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N-P} \tag{4}$$

$$R^2 = \frac{\sum_{i=1}^{n}(MR_i - MR_{pre,i}) \cdot \sum_{i=1}^{n}(MR_i - MR_{\exp,i})}{\sqrt{\left[\sum_{i=1}^{n}(MR_i - MR_{pre,i})^2\right] \cdot \left[\sum_{i=1}^{n}(MR_i - MR_{\exp,i})^2\right]}} \tag{5}$$

It has been accepted that the drying characteristics of biological products in the falling rate period can be described by using Fick’s diffusion equation [12]. The solution of

Fick's law for a slab was according to Equation (6) [31].

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\pi^2\frac{D_{eff}.t}{4L^2}\right) \quad (6)$$

For a long drying period, Equation (6) can be further simplified to only the first term of series [32]. Thus, Equation (6) is written in logarithmic form according to Equation (7):

$$MR = \frac{8}{\pi^2}\exp\left(\pi^2\frac{D_{eff}.t}{4L^2}\right) \quad (7)$$

The Fick's diffusion equation developed for solid objects with slab geometry reported by Crank [33] was applied to the experimental data. The assumption applied in using this equation was that there were uniform initial moisture distribution and negligible external resistance [34]. The equation is as indicated in Equation (8) below:

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \left(\pi^2\frac{D_{eff}.t}{4L^2}\right) \quad (8)$$

Diffusivities are typically determined by plotting experimental drying data in terms of ln (*MR*) versus drying time t in Equation (7) because the plot gives a straight line with a slope according to Equation (9).

$$Slope = -\frac{\pi^2 D_{eff}.t}{4L^2} \quad (9)$$

Or $k = \left[\ln(MR) - \ln\left(\frac{8}{\pi^2}\right)\right]/t$, which is the slope of the straight line which fits the experimental data of $\ln(MR)$ against drying time.

The activation energy in a drying process, E_a is the minimum quantity of energy that must be overcome to make this process realizable. The E_a value is closely related to D_{eff} coefficient and its temperature dependence can be expressed by the Arrhenius model [35].

The origin of the self-diffusion is thermal agitation. The diffusion is thermally activated, and the diffusion coefficient is traditionally calculated by using the Arrhenius law:

$$D_{eff} = D_0\exp\left(-\frac{E_a}{RT_{abs}}\right) \quad (10)$$

By entering the natural logarithm on both terms of the Equation (10), it can be expressed as follows;

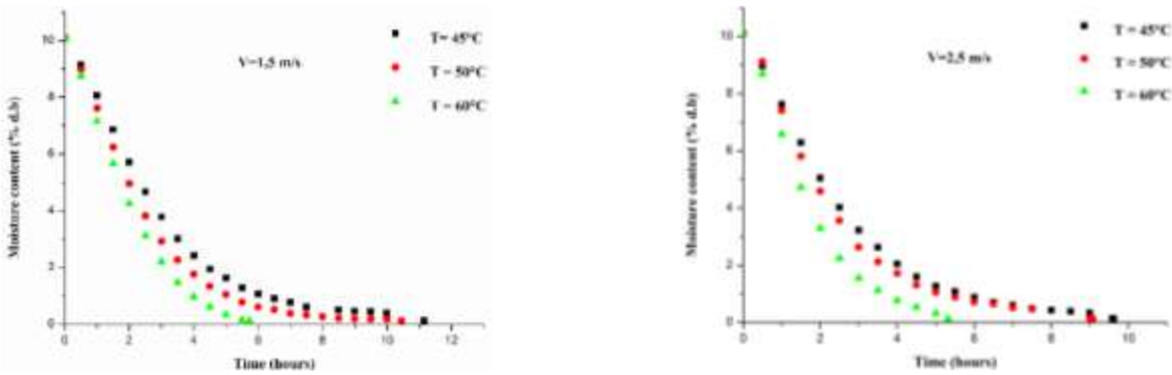
$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{R}\frac{1}{T} \quad (11)$$

The activation energy can be calculated from the straight-line of the plotted curve of effective diffusion in terms on natural logarithmic $\ln(D_{eff})$ against the reciprocal of absolute drying temperature $(1/T)$. $(-E_a / R)$ expressed the value of straight-line fitted on this curve.

2.- Results and discussion

2.1.- Effect of Drying Air Temperature

The experimental curves in (fig. 3-a) show that increasing air drying temperature from 45 to 60°C decreased significantly the drying time (11.16 h, 10.45 h, 5.73 h) to air temperature 45, 50, and 60°C respectively, for air velocity of 1.5 m/s. This influence is due to an increase in the partial vapor pressure of water in the product. Also, an increase in air velocity from 1.5 to 2.5 m/s decreases relatively the drying time as a result of increasing convective heat and mass transfer coefficient between the drying air and the product (for T = 45°C drying time is 11.16 h and 9.62 h, respectively, to 1.5 m/s, 2.5 m/s (air velocity). For T = 50°C it is 10.45, 9.08 hours respectively. Finally, for T = 60°C it fell to 5.73 h and 5.32 h. Therefore, there is a strong function of temperature and a relatively weak function of air velocity. The obtained results showed that air drying temperature has a higher effect on the moisture content reduction, which is similar to Coşkun, *et al.* (2017) [36] conclusion. As was expected, during the initial stages of drying there was a rapid moisture removal from the product (slope of moisture curve in (fig. 3-b) is much higher at the beginning of drying process) which later decreased with an increase in drying time.

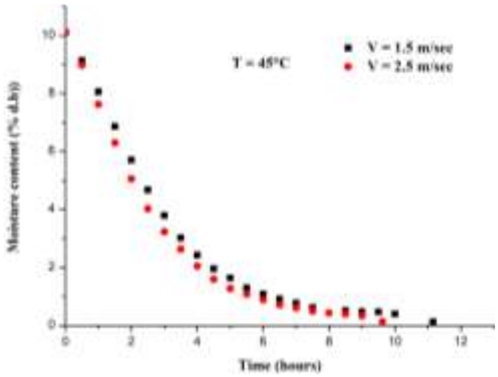


a: V = 1.5 m/s **b : V =2.5 m/s**

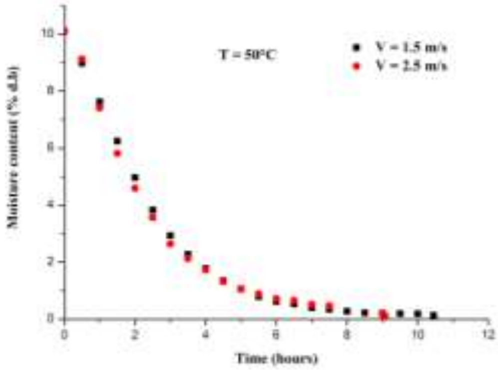
Figure 3.- Effect of drying air temperature with 1.5 and 2.5 m/s air velocity on drying kinetics of tomato paste

3.2.- Effect of Airflow Velocity

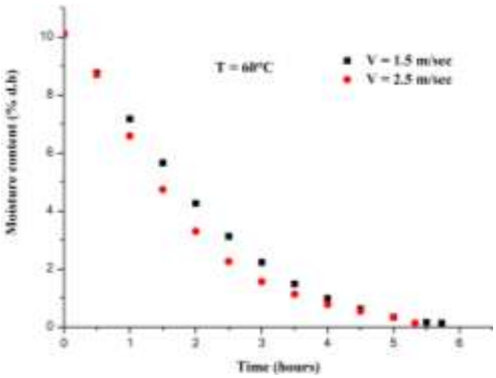
By observing the effect of air velocity on drying kinetics Figures 4.a-c, the results show a slight effect of air velocity at low temperatures compared with high ones. The effect of air velocity increases with increasing drying air temperature. Boughali, *et al.* (2009) confirmed that the air velocity is not an influential parameter as compared with the drying air temperature and the influence decreases with the drying process increasing [37].



a: T = 45 °C



b: T = 50 °C

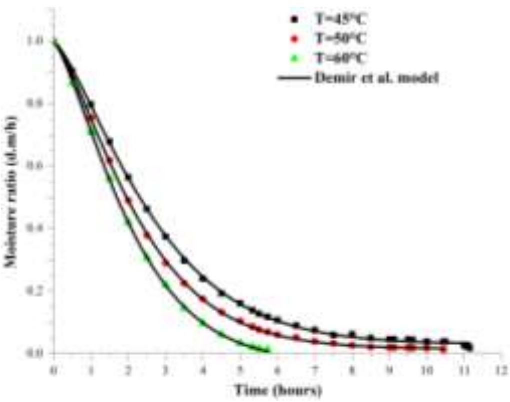


C: T = 60 °C

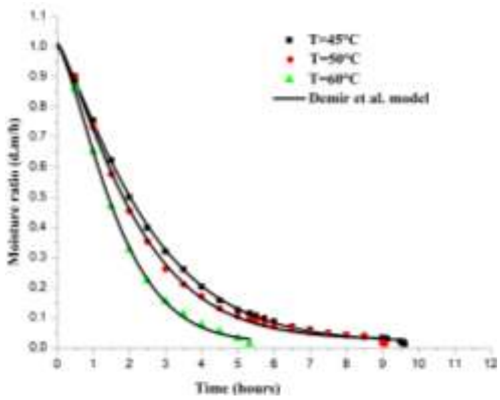
Figure 4.- Effect of air velocity at T= (45, 50, and 60°C) on drying kinetics of tomato paste

2.3.- Statistical Results of Thin Layer Drying Models for Convective Drying

The moisture content of tomato paste was transformed into a dimensionless moisture ratio to perform modeling studies easily. The values of the moisture ratio of tomato paste samples were calculated using equation (2). The moisture ratio values were fitted to nine theoretical drying models listed in (tab. II). The acceptability of the model is based on the correlation coefficient, mean squared deviation, and root means square error. To observe the accuracy of the models, coefficient of determination (R^2), reduced mean squared deviation or chi-square (χ^2) and the root mean square error (RMSE) values are calculated and given in (figs. 5a-b).



a: V = 1.5 m/s



b: V =2.5 m/s

Figure 5.- Moisture ratio versus drying time with V = (1.5 and 2.5 m/s) air velocity

The experimental moisture content data were determined on a dry basis and used for modeling. The moisture content data at each time of the drying process, obtained at different drying temperatures 45, 50, and 60°C and for two levels of air velocity of 1.5 and 2.5 m/s, were converted to the moisture ratio values and fitted versus drying time.

By using regression analysis, the value of correlation coefficient (R^2), the reduced chi-square (χ^2), and Root Mean Square Errors (RMSE) and their coefficients are determined and listed in Tables 3-4.

Based on the range and average values of the statistical parameters for each model, it can be concluded that Demir et al. model, followed by Midilli et al. model, gives the best representation of the experimental data and was applied successfully to describe and predict the behavior of this variety of tomato paste in these conditions.

Generally, the coefficient of correlation coefficient (R^2), the reduced chi-square (χ^2) and Root Mean Square Errors (RMSE) values of Demir et al. model varied from 0.99988 to 0.99993, 0.00001 to 0.000042 and 0.0032 to 0.00649, respectively for dried tomato paste with 1.5 m/s air velocity, and from 0.999440 to 0.99959, 0.000036 to 0.00013 and 0.00602 to 0.01154, respectively with 2.5 m/s air velocity Tables 5-6.

Table III.- Statistical results of the nine selected thin layer drying models at different drying temperatures with 1.5 m/s air velocity

Model	R^2	RMSE	(χ^2)	Model coefficients
		Drying temperature = 45°C		
Lewis	0.98932	0.02765	0.00076	k=0.33323
Page	0.99623	0.01668	0.00028	k=0.25971, n=1.18276
Modified page	0.99623	0.01668	0.00028	k=0.31989, n=1.18194
Henderson and Pabis	0.99331	0.02221	0.00049	a=1.06849, k=0.35292
Logarithmic	0.99335	0.02248	0.00051	a=1.06962, c=0.34884, k=-0.00338
Wangh and Singh	0.98001	0.03839	0.00147	a=-0.22723, b=0.01297
Diffusion approach	0.99101	0.02613	0.00068	a=8.842e12, b=1, k=0.25371
Demir *et al.*	0.99946	0.00649	0.000042	a=0.96882, b=0.03132, k= 0.24058, n=1.322
Midilli *et al*.	0.99927	0.00755	0.000057	a=1.00295, b=0.00276, k=0.2416, n=1.28765
		Drying temperature = 50°C		
Lewis	0.98787	0.03076	0.00094	k=0.40179
Page	0.99877	0.00998	0.000099	k=0.29965, n=1.25298
Modified page	0.99877	0.00998	0.000099	k=0.38223, n=1.25227
Henderson and Pabis	0.99235	0.02487	0.00062	a=1.07326, k=0.42697
Logarithmic	0.9932	0.02388	0.00057	a=1.07966, c=-0.01517, k=0.40639
Wangh and Singh	0.98075	0.03943	0.00156	a=-0.26288, b=0.01689
Diffusion approach	0.98787	0.03187	0.00102	a=1, b=1, k=0.40175
Demir *et al.*	0.99988	0.0032	0.00001	a=0.98401, b=0.01671, k=0.29334, n=1.32038
Midilli *et al.*	0.99983	0.00381	0.000014	a=1.00209, b=0.00167, k=0.29307, n=1.30165
		Drying temperature = 60°C		
Lewis	0.9727	0.05604	0.00314	k=0.48116

Page	0.99946	0.00824	0.000068	k=0.33256, n=1.39904
Modified page	0.99946	0.00824	0.000068	k=0.45523, n=1.39943
Henderson and Pabis	0.97976	0.05022	0.00252	a=1.07955, k=0.515
Logarithmic	0.99516	0.02564	0.00066	a=1.20271, c=-0.16299, k=0.36219
Wangh and Singh	0.99829	0.01462	0.00021	a=-0.34783, b=0.03069
Diffusion approach	0.9727	0.06092	0.00371	a=1, b=1, k=0.48127
Demir *et al.*	0.99993	0.00331	0.000011	a=1.02164, b=-0.02481, k=0.32827, n=1.34031
Midilli *et al.*	0.99991	0.00358	0.000013	a=0.99645, b=-0.00366, k=0.332, n= 1.35146

Table IV.- Statistical results of the nine selected thin layer drying models at different drying temperatures with 2.5 m/s air velocity

Model	R^2	RMSE	(χ^2)	Model coefficients
		Drying temperature = 45°C		
Lewis	0.99231	0.02471	0.000610	k=0.3762
Page	0.99871	0.01031	0.00011	k=0.30376, n=1.17337
Modified page	0.99871	0.01031	0.00011	k=0.36227, n=1.17282
Henderson and Pabis	0.99545	0.01936	0.00037	a=1.05881, k=0.3957
Logarithmic	0.996	0.01853	0.00034	a=1.06497, c=-0.01413, k=0.37813
Wangh and Singh	0.98537	0.03474	0.00121	a=-0.25704, b=0.01653, k=0.3762
Diffusion approach	0.99231	0.02568	0.00066	a=1, b=1, k=0.3762
Demir *et al.*	0.99959	0.00602	0.000036	a=0.9861, b=0.01873, k=0.30171, n= 1.23192
Midilli *et al.*	0.99952	0.00653	0.000043	a=1.00609, b=0.00176, k=0.30046, n=1.21507
		Drying temperature = 50°C		
Lewis	0.98991	0.02957	0.00087	k=0.41348
Page	0.99682	0.017	0.00029	k=0.33804, n=1.1824
Modified page	0.99682	0.017	0.00029	k=0.39967, n=1.18171
Henderson and Pabis	0.99388	0.02358	0.00055	a=1.0647, k=0.43761
Logarithmic	0.99412	0.02366	0.00056	a=1.06978, c=-0.01017, k=0.4242
Wangh and Singh	0.97629	0.04639	0.00215	a=-0.27867, b=0.01938
Diffusion approach	0.98991	0.03101	0.00096	a=1, b=1, k=0.41347
Demir *et al.*	0.99867	0.01154	0.00013	a=0.98733, b=0.02725, k=0.34553, n=1.25496
Midilli *et al.*	0.99841	0.01264	0.00016	a=1.01679, b=0.0027, k=0.34376, n=1.22346
		Drying temperature = 60°C		
Lewis	0.98031	0.04774	0.00228	k=0.5523
Page	0.99913	0.01054	0.00011	k=0.43185, n=0.43185
Modified page	0.99913	0.01054	0.00011	k=0.53197, n=1.33002
Henderson and Pabis	0.98604	0.04216	0.00178	a=1.06939, k=0.5875
Logarithmic	0.99245	0.03267	0.00107	a=1.13575, c=-0.08892, k=0.47854
Wangh and Singh	0.99443	0.02663	0.00071	a=-0.40722, b=0.04262
Diffusion approach	0.98031	0.05278	0.00279	a=1, b=1, k=0.5523

Demir *et al.*	0.99944	0.00947	0.000089	a=0.98974, b=0.01607, k=0.44204, n=1.36656
Midilli *et al.*	0.99939	0.00986	0.000097	a=1.00639, b=0.00251, k=0.43837, n=1.3528

Table V.- Statistical results of DEMIR *et al*. model with 1.5 m/s air velocity

Air velocity, 1.5 m/s							
Temperature (°C)	**A**	**b**	**K**	**n**	**R^2**	**RMSE**	**(χ^2)**
45	0.96882	0.03132	0.24058	1.322	0.99946	0.00649	0.000042
50	0.98401	0.01671	0.29334	1.32038	0.99988	0.0032	0.00001
60	1.02164	0.02481	0.32827	1.34031	0.99993	0.00331	0.000011

Table VI.- Statistical results of DEMIR *et al.* model with 2.5 m/s air velocity

Air velocity, 2.5m/s							
Temperature (C°)	**A**	**b**	**K**	**n**	**R^2**	**RMSE**	**(χ^2)**
45	0.9861	0.01873	0.30171	1.23192	0.99959	0.00602	0.000036
50	0.98733	0.02725	0.34553	1.25496	0.99867	0.01154	0.00013
60	0.98974	0.01607	0.44204	1.36656	0.99944	0.00947	0.000089

The constant values of Demir et al. model for different conditions were regressed against. Regression analysis for these parameters yielded the following relationships:

$$a = 0.99523 - 0.00008T + 0.00955333v - 0.008435T^2 - 0.00174T \times v$$

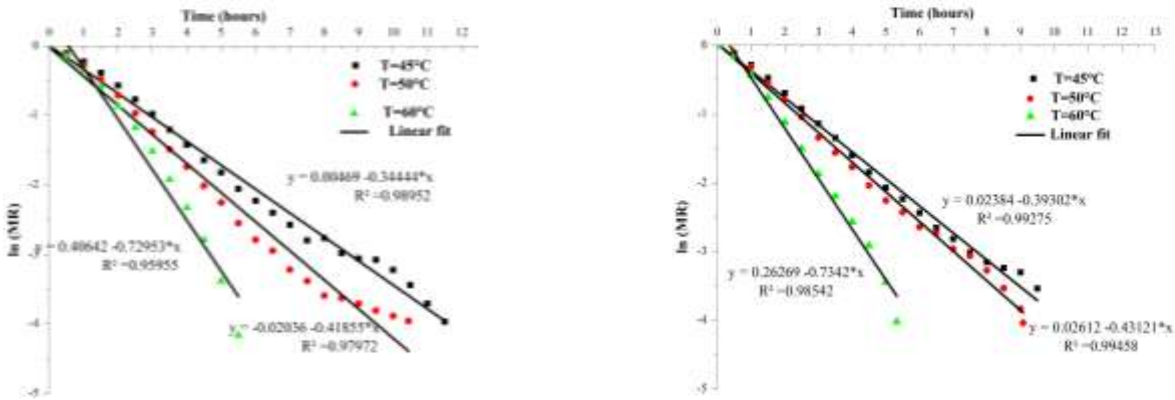
$$b = 0.028065 + 0.0033T - 0.00261167v - 0.008375T^2 - 0.00197T \times v$$

$$k = 0.284425 - 0.022035T + 0.032095v + 0.06123T^2 - 0.04813T \times v$$

$$n = 1.33115 - 0.050015T + +0.0069833v - 0.0377T^2 - 0.017305T \times v$$

3.4.- The Effective Moisture Diffusivities and Activation Energy

The Ln (MR) versus time (h) for a different level of air velocity and drying temperature is shown in Figures 6.a-b. For drying temperatures of 45, 50, and 60°C, respectively. All the figures show that the drying of tomato paste occurred in the falling rate period, in other words, the liquid diffusion is by the dry win force controlling the drying process [10]. (figs. 6-a.b) plotted curves show that the increase in temperature and air velocity increases the slope of a straight line, in other words, the effective moisture diffusivity increases.



a: V = 1.5 m/s **b: V =2.5 m/s**

Figure 6.- Effect of drying temperature on effective moisture diffusivity in tomato paste with 1.5 and 2.5 m/s air velocity

Figure 7-a presents the values of effective moisture diffusivities versus drying time for drying temperatures of 45, 50, and 60°C. Effective moisture diffusivities were found to be 2.18341 10^{-9}, 2.65319 10^{-9} and 4.62449 10^{-9} m²/s respectively, for 1.5 m/s air velocity, and 2.49135 10^{-9}, 2.7334 10^{-9} and 4.65409 10^{-9}m²/s respectively, for 2.5 m/s air velocity. The drying air temperature has a higher effect on moisture diffusivity. A lot of recent studies confirmed this result such as ours [38-40]. (fig. 7-b) displays thevs ln (D_{eff}) vs 1/T for T =45, 50 and 60 °C, respectively for air drying velocities 1.5 and 2.5 m/s respectively. According to the curves. The obtained findings revealed that increasing air drying velocity and drying temperature affect directly the slope value, in other words, the activation energy. According to the slopes of (fig. 7-b), activation energies were found to be 44.836 and 38.159 Kj/mol for air velocities 1.5 and 2.5 m/s respectively. (tab. IIV) shows the activation energy and the pre-exponential factors of the Arrhenius equation for both drying temperatures with air drying velocities.

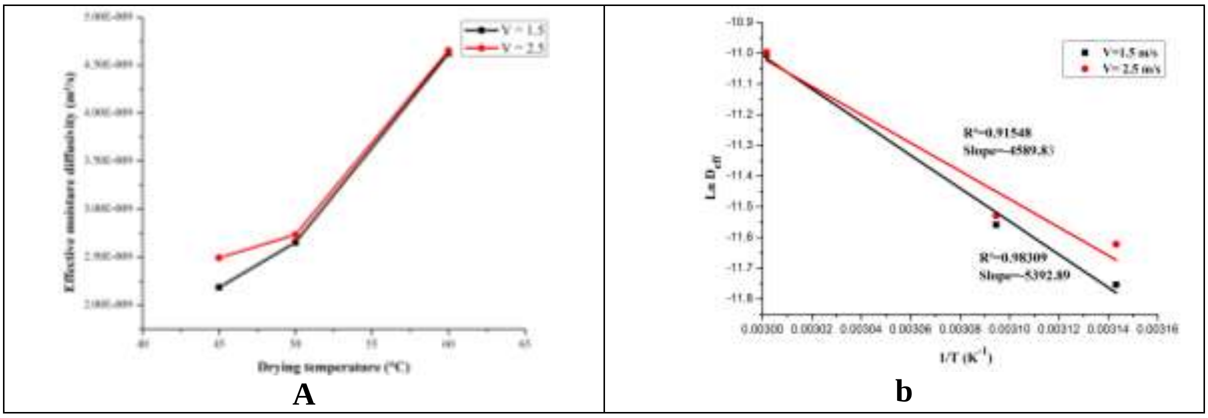


Figure 7-a.- Effect of drying temperature and air velocity on effective moisture diffusivity and b: activation energy

Table VII.- Activation energy and effective diffusivity coefficient of tomato paste

V = 1.5 m/s	**Equation**	**Activation energy (kj/mol)**
T = 45 °C	$D_{eff} = 0.0502.\exp\left(\frac{-5392}{T+273.15}\right)$	
T = 50 °C	$D_{eff} = 0.0496.\exp\left(\frac{-5392}{T+273.15}\right)$	44.836
T = 60 °C	$D_{eff} = 0.0496.\exp\left(\frac{-5392}{T+273.15}\right)$	
	V = 2.5 m/s	
T = 45 °C	$D_{eff} = 0.0046.\exp\left(\frac{-5392}{T+273.15}\right)$	
T = 50 °C	$D_{eff} = 0.0040.\exp\left(\frac{-5392}{T+273.15}\right)$	38.159
T = 60 °C	$D_{eff} = 0.0045.\exp\left(\frac{-5392}{T+273.15}\right)$	

Conclusion

The present study was carried out to valorize the surplus of the local tomato production using hot air-drying methods. The tomato paste in the form of organic matter was invested. The drying tomato paste was then established using an automated laboratory drying system (LETTM, El-Manar University of Tunis).

The effects of two drying parameters (air temperature, air velocity) on drying time and drying kinetics of dried tomato paste were investigated. They were conducted under air conditions as the constant relative humidity of 16%, temperatures 45°C, 50°C, 60°C with an airflow velocity of 1.5 and 2.5m/s. Obtained drying kinetics showed only falling periods and led to drying time ranged between 11.16 and 5.32 hours.

Evaluation of the suitable mathematical models, describing thin-layer drying behavior of tomato paste with several drying conditions revealed that Demir et al. model was the best fitted among nine investigated models, followed by Midilli et al. model.

The highest moisture diffusivities were 4.62449 10^{-9} m²/s and 4.65409 10^{-9} m²/s for the highest air drying temperature 60°C, for both air velocities, respectively. The activation energies were found to be 44.836 and 38.159 Kj/mol for air velocities 1.5 and 2.5 m/s respectively.

Nomenclature

M_t	The moisture content at any time (kg water/kg d.m)
M_e	Equilibrium moisture content (kg water/kg d.m)
M_0	Initial moisture content (kg water/kg d.m)
MR	Moisture ratio, dimensionless
D_{eff}	Effective moisture diffusivity (m²/s)
E_a	The activation energy (kJ/mol)
D_0	The pre-exponential factor of the Arrhenius equation (m²/s)
R_g	The perfect gas constant (8.314 J/ mol.K)
T	Air drying temperature (°C, K)
v	Air velocity (m/s)
L	Slab thickness (m)
a,b,c,n,k	Constants of models
t	Drying time (h)

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