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CONVECTIVE DRYING OF CHERRY TOMATO: STUDY OF SKIN EFFECT

R. KHAMA[1,2,]*, F. AISSANI[1], R. ALKAMA[3], L. BENNAMOUN[4],
L. FRAIKIN[5], T. SALMON[5], E. PLOUGONVEN[5], A. LEONARD[5]

[1] Laboratoire de Génie de l'Environnement, Faculté de Technologie,
Université de Bejaia, 06000 Bejaia, Algeria
[2] Univ. Ouargla, Fac. Sciences Appliquées, Lab. Génie des Procédés,
Ouargla 30000, Algeria
[3] Laboratoire de Génie Électrique, Faculté de Technologie,
Université de Bejaia, 06000 Bejaia, Algeria
[4] Bioenergy and Bioproducts Research Laboratory, Department of Mechanical Engineering
Faculty of Engineering, University of New Brunswick
PO BOX: 4400, Fredericton, NB, Canada E3B 5A3
[5] Laboratory of Chemical Engineering, University of Liège 4000 Liège, Belgium
*Corresponding Author: redkhama@yahoo.fr

Abstract

A whole single cherry tomato was dried in a forced convective micro-dryer. The experiments were carried out at constant air velocity and humidity and temperatures of 50, 60, 70 °C. In order to study the effect of the skin, two sets of experiments were performed using a tomato with and without skin (easily removed). Shorter drying times were obtained when increasing drying temperatures as well as when removing sample skin. X-ray microtomography, a non-destructive 3D imaging technique was used to follow shrinkage of the samples. This phenomenon was introduced in the modelling part of this study. Analytical solutions of the Fick'law were used to determine the diffusion coefficient at the three temperatures studied, and then the activation energy was obtained through fitting the Arrhenius equation. The skin effect was clearly evidenced by showing that the mass transfer parameter values of an original tomato with skin were largely smaller than the one without skin. Indeed, the moisture effective diffusivity ranged from 2.56×10^{-11} to 7.67×10^{-11} $m^2\cdot s^{-1}$ with activation energy of 50430 $J\cdot mol^{-1}$ for tomato with skin and ranged from 4.59×10^{-10} $m^2\cdot s^{-1}$ to 6.73×10^{-10} $m^2\cdot s^{-1}$ with activation energy of 17640 $J.mol^{-1}$ for tomato without skin.

Keywords: Micro dryer, Skin, Cherry tomato, Diffusion model, Shrinkage effect.

Nomenclatures

D_{eff}	Moisture diffusion coefficient, $m^2.s^{-1}$
DR	Drying rate, kg water/kg dry matter.s
D_0	Constant in Equation (5), $m^2.s^{-1}$
E	Activation energy, J/mol
M_d	Dry mass, kg
$M_h(t)$	Wet mass of the product at the moment t, kg
R	Perfect gas constant = 8.314 J/ K.mol
T	Temperature, K or °C
t	Time, s
t_f	Final time, s
V	Actual volume of the product, m^3
V_0	Initial volume of the product, m^3
X	Actual water content, kg water / kg dry matter
X_0	Initial water content, kg water / kg dry matter
$X(t)$	Water content at the moment t, kg water / kg dry matter
$X(t+\Delta t)$	Water content at the moment ($t+\Delta t$), kg water / kg dry matter

Greek Symbols

Δt	Step of time, s

1. Introduction

The tomato is one of the most important horticultural crops in the world. This crop is utilized in the manufacture of various products, such as juice, puree, paste, ketchup, sauce and soups [1]. In terms of human health, tomato fruit is a major component of daily meals in many countries and constitutes an important source of minerals, vitamins, and antioxidant compounds [2]. Dried tomato is considered as a delicatessen food adopted in many national cuisines. In the last decade, it has been promoted as an ingredient of fresh green salads or recipes [3].

The interest in the production of dried tomatoes is increasing due to the possibility of using them in pizza toppings, pestos, snacks and other dishes [4]. Receipts such as: dried tomato tapenade, zucchini and tomato gratin with porcini mushrooms of dried tomato with porcini mushrooms and county, balls of pizza with old Dutch Gouda, bacon and dried tomatoes, breadsticks with dried tomatoes, macaroni gratin with dried tomatoes, dried tomatoes in olive oil, cake with tomato and mozzarella and risotto with dried tomatoes, pepper and pecorino which also used dried tomatoes with skin as well as dried tomatoes without skin.

Specifically, the cherry tomato (L. Esculentum var. Cerasiforme) is considered to be an ancestral variety of tomato, based on the fact that both its size and its shape (2 to 2.5 cm in diameter) are intermediary between wild and domesticated tomatoes [5]. The nutritional and health properties of certain tomato components, such as lycopene, make it interesting to use osmotic dehydration to obtain stable products that maintain their quality attributes and improve sensorial acceptability.

Drying is an energy intensive process that results in the removal of moisture from a body by evaporation. This operation is largely used in the food industry to ensure product transformation or conservation, with an impact on production cost. For example, the energy cost for plum drying constitutes about a quarter of the total cost of their production [6]. Ideally, the drying process should be optimized in order to utilize a minimum amount of energy for maximum moisture removal [7], but this is far from the reality, lots of dryers being operated empirically. In particular, the choice of the temperature should be carefully done. Indeed, increasing the drying temperature will usually accelerate the drying process, leading to decreasing drying duration, but the loss in organoleptic properties (texture, colour, density, porosity, and adsorption characteristics) as well as nutritional values (vitamins, minerals, proteins, carbohydrates, dietary fiber) of the product during this process may not compensate for the economic advantage gained in the reduction of processing time [8]. Increasing drying time and temperature cause the darkening of the tissue [9]. Indeed, high temperatures or long drying times in conventional air drying not only can cause serious damage to the product, but reduces the rehydration capacity of the dried product too [10]. Moreover, one cannot neglect that a high temperature also means a high consumption of energy during drying. Then the optimization of tomato drying in terms of both maximizing the drying rate and minimizing heat damage requires low temperatures for short times [11]. This is why this work considers moderate temperatures compatible with solar drying where the average air temperature, with a low humidity, is equal to 40 °C.

In this paper, the study is focused on the drying of cherry tomato, to investigate the influence of the skin on water removal. During drying, X-ray microtomography was proposed as an advanced characterization tool to investigate the evolution of size, shape and texture of tomato during the course of drying. To our knowledge, it seems that few studies related to the skin effect during the drying of fruits were done until now. We can quote two studies in peeled and unpeeled products. The first study was on tomato [12] and the second study on whole figs [13].

2. Literature review

The tomato was, for a long time, the concern of many scientific researchers because of its benefactions and its wide use. In particular, a large number of studies dedicated to drying can be found. In the study of Szentmarjay et al. [14], tomato concentrate and baker's yeast suspension were dried in a laboratory scale “mechanically spouted bed dryer” with inert packing. The diffusion resistance was considered as negligible and drying was performed at "quasi -constant" rate. In the investigation of Karatas and Esin [15], the drying mechanism and the diffusion coefficient of water in spherical droplets of tomato concentrates were successfully interpreted and modeled using Fick's law. The effective moisture diffusivity was estimated from the drying rate curves and expressed by an Arrhenius relation. In the paper of Xanthopoulos et al. [3], the drying kinetics and the effective water diffusivity of tomato halves during oven drying were investigated. This study was carried out for three drying temperatures (45, 55, and 65°C) and for salted and non-salted samples.

Study of the drying of tomato can also be found in the work of Gaware et al. [16] where five different methods were used to dehydrate tomato slices, viz., hot air, solar cabinet, heat pump, microwave vacuum, and freeze drying. The drying characteristics of tomatoes were also investigated at 55, 60, 65 and 70°C with air flow rate of 1.5 m/s by Doymaz [17]. Drying experiments were performed in a laboratory scale hot-air dryer and then a diffusion model was used to describe the moisture transfer and the effective diffusivity at each temperature was determined.

3. Materials and Methods

3.1. Materials

3.1.1. The micro-dryer

Drying experiments were carried out in a micro-dryer specially designed for handling small individual samples with mass ranging between 1 and 20 g. The micro dryer unit is described in Fig. 1 [18]. It is composed of two parts: the air conditioning and feeding system and the drying chamber. Air is fed from the laboratory compressed air network. A pneumatic valve connected to a mass flowmeter controls its flow rate. Air can be humidified by adding steam generated by a steam generator, heated up to the required temperature by passing through a heating channel and then directed to the drying chamber. Air humidity, temperature and flowrate are continuously monitored and controlled. The tomato was put in the drying chamber on a supporting grid linked underneath to a precision weighing device (BP 150 from Sartorius, Germany; accuracy: 0.001 g). The sample surroundings is such that drying can occur on the whole external surface. The weighing device is connected to a PC that records the mass every one second. The micro-drier can be operated at temperatures ranging between 20 and 180 °C. The air flowrate ranges between 30 and 300 Nl/min (i.e., air superficial velocities in the drying chamber between 0.3 and 5 m/s). The maximum steam production at the highest air flowrate (300 Nl/min) achieves an absolute humidity content of about 0.2 kg/kg dry air. Corresponding air relative humidity depends on selected operating temperature and flowrate. The results reported in this paper have been obtained at a constant speed of 0.42 m/s, with air at ambient humidity without any vapour addition and three drying temperature (50, 60, 70°C). A drying assay was monitored by continuously weighing the sample. One run is characterized by a curve representing the sample weight vs. time.

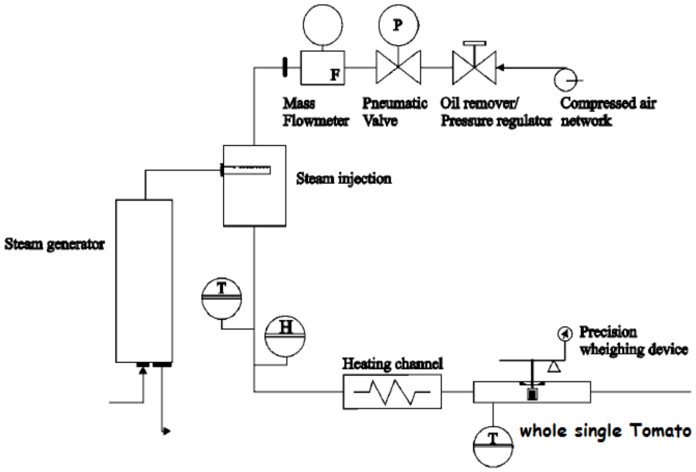


Fig. 1. Detailed schema of the convective dryer [18].

3.1.2. The X-ray tomographic device

Shrinkage was obtained by using an X-ray tomographic device: ''Skyscan-1172 X-ray scanner'' (Skyscan, Belgium). The X-ray source operates at 100 kV and 250 mA. The detector is a 3D, 4000×2300 pixels, 12-bit CCD camera with a spatial resolution of from 34 to 2-3 µm. The sample can be either rotated in a horizontal plane or moved vertically in order to get scans at different vertical positions [18, 19]. The acquisition protocol was defined in order to scan the whole tomato sample and to characterize its 3D structure.

Figure 2 shows the significant variation of volume between the beginning and the end of drying of a cherry tomato with skin, i.e. the dried tomato were skin-on, obtained after 3D reconstruction of images obtained by microtomography. Shrinkage curves were determined from these 3D images by calculating the volume at increasing drying times.

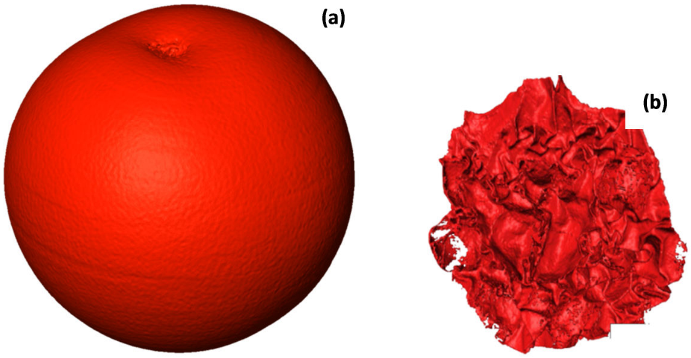


Fig. 2. 3D reconstruction of images of cherry tomato (with skin) obtained by microtomography: (a) Tomato before drying, (b) Tomato after drying.

3.2. Method

3.2.1. Data analysis

The drying process of the cherry tomato was continued until the product achieved its final mass, corresponding to the stabilization of the value recorded by the balance. After each drying experiment, the dry mass of tomato was determined by putting the entire dried product, during 24 h, in a regulated drying oven at 105°C.

The water content on a dry basis at any time t was defined by using Eq. (1) [20].

$$X(t)=\frac{M_h(t)-M_d}{M_d} \tag{1}$$

The drying rate during the drying process was determined by using Eq. (2).

$$DR=\frac{X(t)-X(t+\Delta t)}{\Delta t} \tag{2}$$

3.2.2. Shrinkage determination

X-ray microtomography parameters were chosen to produce images with a pixel size of 34.55 µm. The X-ray source was set at 100 kV and 100 µA, and to reduce beam hardening a 0.5 mm Aluminum filter was used. With these parameters, exposure time for each projection was set at 316 ms to obtain grey levels in the correct range of the detector. The rotation step was set at 0.7° over 360°, resulting in 514 angular steps and at each step 2 projections were taken and averaged in order to cancel out noise. The tomograph has the option of performing multiple vertically-aligned scans and stitching the projections together, for reconstructing objects higher than the field of view. This option was used due to the size of the tomatoes.

After scanning, the stitching, mentioned previously, and reconstruction is performed using Skyscan's NRecon software (v. 1633), giving 2D grey level cross sections. The software has a built-in ring artifact correction option, which was used here. A simple segmentation process was applied to the reconstructions. First a median filter, with a 5-pixel ball as structuring element, is used. This removes most of the remaining noise, without altering the visible phases (sample and void). Then watershed segmentation is used on the image gradient, with markers for sample and void set beforehand by thresholding.

Stacking all the 2D processed images, results in a 3D binary image, in which the pixels are either assigned to the sample or the void. A simple connected component analysis of the void phase can highlight the pores inside the tomato, when these are present. Pixel counting allows measuring the volumes of the different phases.

3.2.3. Modelling

The shrinkage has to be taken into account during the mathematical modelling, in particular for the determination of the mass transfer parameters. In this study, the shrinkage was introduced through calculation of the variations in the different physical parameters, such as porosity and the characteristic dimensions, during drying. The evolution of these parameters was expressed as a function of the product's moisture content, as it was done in a recent work of Bennamoun et al. [21]. According to the papers of Bennamoun et al. [22, 23] and Azzouz et al. [24], the shrinkage was assumed to be linear with water content. Then the shrinkage curves were obtained through a linear interpolation between initial and final volume, obtained by microtomography.

4. Results and discussion

4.1. Determination of the shrinkage coefficients

The shrinkage curves obtained by microtomography are reported in Fig. 3 and then the shrinkage coefficients of volume followed a linear trend:

In the case of a cherry tomato with skin:

$$V / V_0 = 0.9243 \; X / X_0 + 0.0757 \tag{3}$$

In the case of a cherry tomato without skin:

$$V / V_0 = 0.9992 \quad X / X_0 + 0.0008 \tag{4}$$

The reduction in volume, i.e., diameter, was observed during drying of cherry tomato. Experimental results of the volume decrease for cherry tomato along with the drying time are presented in Fig. 4 where the evolution of the volumetric ratio (ratio of the actual volume to the initial volume) of the product according to dimensionless time (ratio of the actual time to the final time) can be seen. It was observed that the percentage of shrinkage was much higher and more rapid for the cherry tomato without skin. Cherry tomato without skin lost already half of its volume after the first 14 % of the total drying time but half of the volume of the fruit with skin was lost only after 39 % of total drying time.

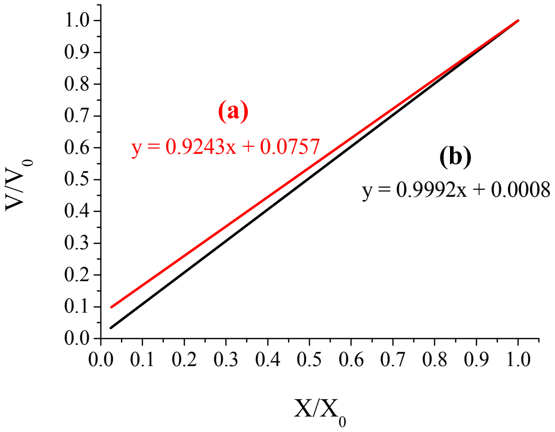


Fig. 3. Experimental results of the volume decrease for cherry tomato during drying at 60 °C: (a) With skin (b) Without skin.

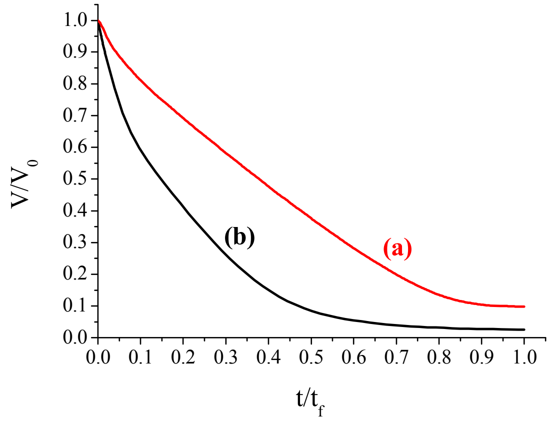


Fig. 4. Experimental results of the volume decrease for cherry tomato vs. drying time at 60 °C: (a) With skin (b) Without skin.

4.2. Determination of the drying kinetics

Figure 5 shows the drying curves X/X_0= f(t), obtained for the 3 investigated temperatures of 50, 60, 70 °C and the two types of tomato samples. They express the evolution of the dimensionless moisture (ratio of the actual moisture content to the initial moisture content) of the product according to time. The effect of the temperature on the kinetics is very clear, as found by several researchers as in [17, 25], indeed drying time was shorter by increasing this parameter but it was much shorter if the skin of the fruit was removed. In the case of the tomato with skin, the drying time of the cherry tomato, at 50°C, was 1098000 s (305 h) where as it was 565200 s (157 h) at 70°C (the half); on the other hand, for tomato without skin, for the same temperatures, drying times were of 97200 s (27 h) and 64800 s (18 h) respectively. So the drying time was divided by approximately 11.5 at 50°C and by approximately 8 at 70°C when the skin was removed.

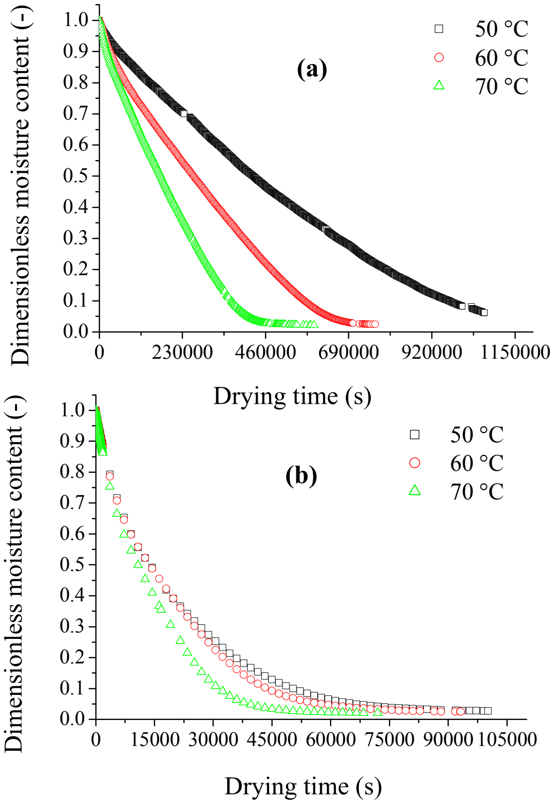


Fig. 5. Influence of the temperature on the moisture ratio during convective drying of cherry tomato: (a) With skin (b) Without skin.

Figure 6 shows the drying rate vs. moisture content curves of tomato at the selected temperatures: with and without skin. In Fig. 6(a), the effect of the temperature can also be clearly observed, especially between 60 and 70°C, with higher drying rates throughout the drying process. This figure also shows a very short adaptation phase followed by a dominant falling drying rate phase which seems to be divided into three sub-periods. Drying of most fruits and vegetables occurs, generally, in the falling rate period. Similar results were obtained by Aktaş et al. [26] and Giovanelli et al. [27].

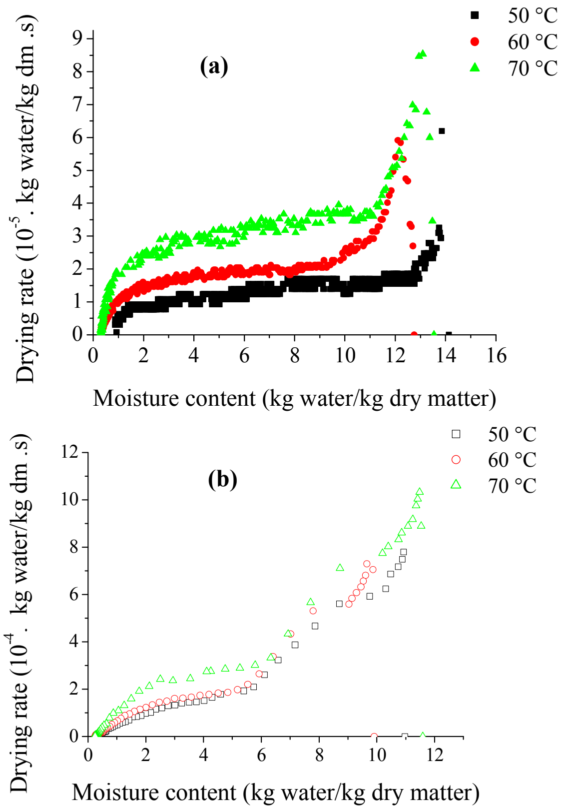
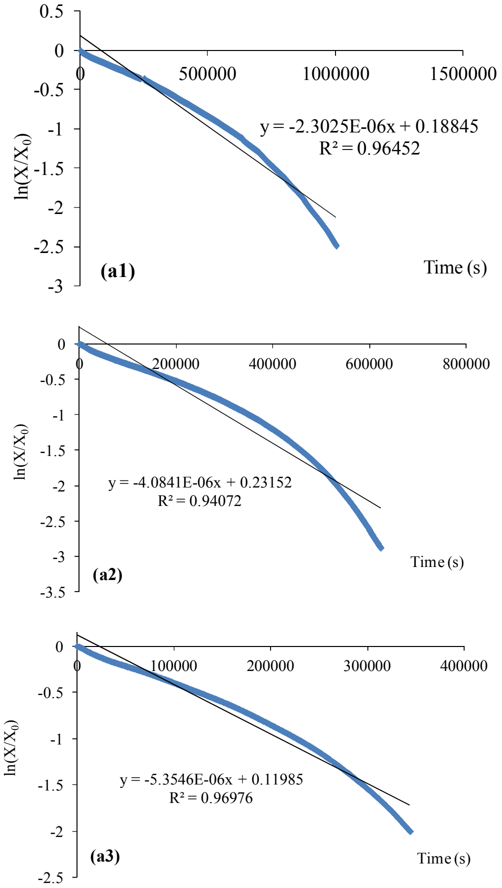


Fig. 6. Influence of the temperature on the drying rate during convective drying of cherry tomato: (a) With skin, (b) Without skin.

As already noted, when the drying temperature was increased, the drying time of fruit decreased (Fig. 5), because the drying rate increased (Fig. 6). But the significant observation and the interesting result found are the quantification and the qualification of the drying temperature effect on drying kinetics, while comparing two convective dryings of cherry tomato: with and without skin. Consequently, the skin effect was clearly highlighted: an increase in drying temperature had less influence when the skin was removed. Indeed, curves obtained at 50 °C and 60 °C were almost superimposed and not very distant from the one at 70 °C, conversely to the results obtained for the original tomato with skin. The benefit of drying without skin is still very clear in Fig. 6(b), which shows drying kinetics during cherry tomato convective drying without skin. Drying rates of the two cases were incomparable: the maximum values of drying rates were, respectively, 10.06×10^{-4} kg water/kg dm.s and 8.61×10^{-5} kg water/kg dm.s for cherry tomato without and with skin. However, removal of skin decreased, appreciably, drying time by having the same effect of high drying temperature. Consumption in energy was also reduced by the not-need for a high drying temperature and preservation of the dried fruit quality has more chance.

4.3. Determination of the internal diffusion coefficient

The plots of the experimental results as $\ln(X/X_0)$ versus time, for different temperatures in the two studied cases: with and without skin, are shown in Fig. 7. Crank analytical solution [28], with introduction of sample shrinkage, was used to determine the mass transfer diffusion coefficient. The values obtained at the different temperatures are summarized in Table 1.



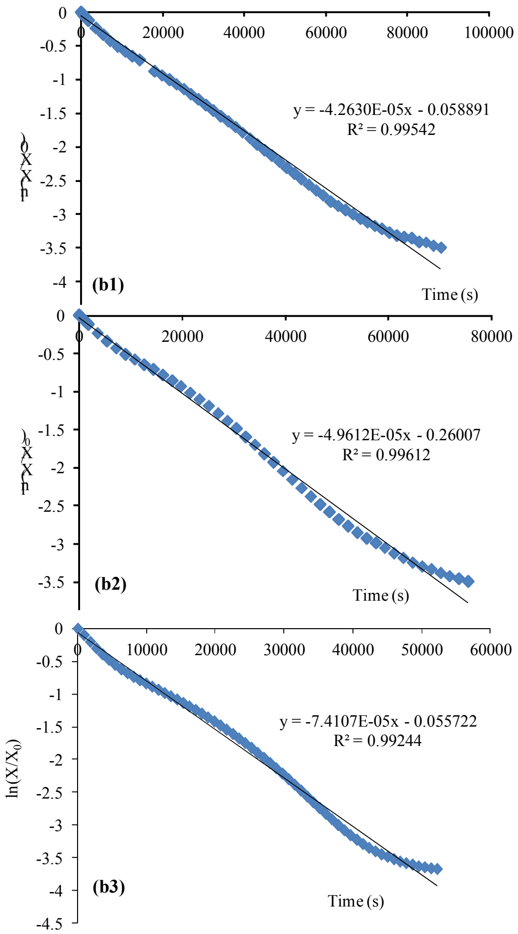


Fig. 7. Variation of the moisture with time for different temperatures. (a1) With skin at 50°C (b1) Without skin at 50 °C (a2) With skin at 60 °C (b2)Without skin at 60 °C (a3)With skin at 70 °C (b3)Without skin at70 °C

Table 1. Variation of the diffusion coefficient with temperature.

Temperature (°C)	$D_{eff}\times10^{-11}$ (m^2.s^{-1}) **With skin**	$D_{eff}\times10^{-10}$ (m^2.s^{-1}) **Without skin**
50	2.56	4.59
60	4.12	6.05
70	7.67	6.73

In the analytical solutions proposed by Crank [28], the moisture diffusion coefficient was determined and written as function of the drying air temperature under Arrhenius form permitting by this way the calculus of the activation energy (Eq. (5)).

$$D_{eff} = D_0 \exp\left(-\frac{E}{RT}\right) \tag{5}$$

As indicated by the values found in Table 1, the moisture diffusion coefficient increased with the drying temperature, as found by several researchers as [2, 17, 29]. It proved, in our study, that this coefficient was much more significant if the skin of cherry tomato was removed. However, the less important values of the moisture diffusion coefficient reflect well the resistance of the skin during the process of drying. At 50°C, for example, D_{eff} (Without skin) ≈ 18 × D_{eff} (With skin) but this ratio decreases if the temperature increases; At 70°C: D_{eff} (Without skin) ≈ 8.8 × D_{eff} (With skin). In addition, Fig. 8 shows the variation of the mean value of moisture diffusion coefficient with air temperature. The constant D_0 and Activation energy (E), for the two cases with and without skin, were deduced and the results are shown in Table 2.

Table 2. Determination of the diffusion coefficient parameters.

Cherry tomato	ln (D_0) ($m^2.s^{-1}$)	E (J/mol)
With skin	- 5.64	50430
Without skin	- 14.91	17640

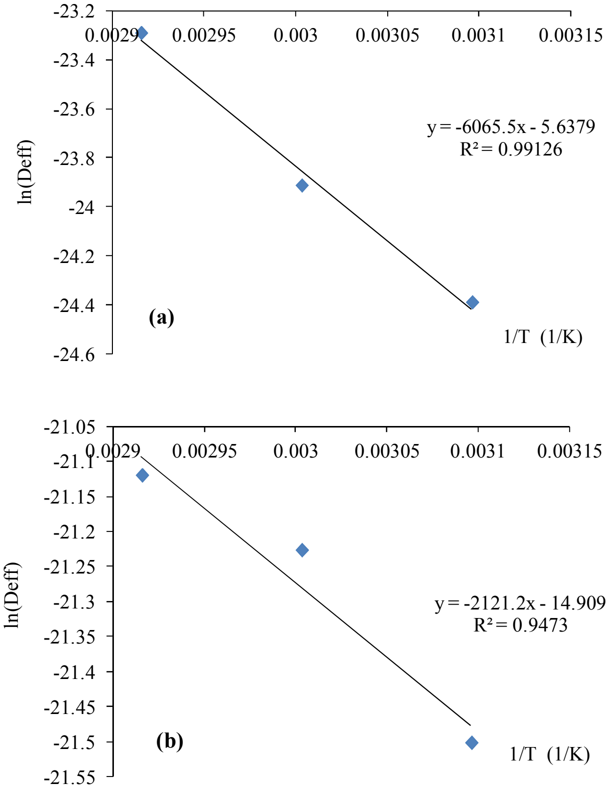


Fig. 8. Determination of the diffusion coefficient parameters.
(a) With skin (b) Without skin

The values found in this study were in good agreement with those found by Wang et al. [25] for the same fruit (cherry tomato) and at the same temperatures (50, 60 and 70°C); Indeed, in the study of Wang et al. [25], the moisture effective diffusivity of cherry tomato drying ranged from 5.49×10^{-10} to 27.54×10^{-10} $m^2.s^{-1}$ with activation energy of 51.09 kJ/mol.

The values of effective diffusivity coefficients experimentally determined for tomato slices using five different methods, viz., hot air, solar cabinet, heat pump, microwave vacuum, and freeze drying were 5.90×10^{-9}, 3.86×10^{-9}, 3.61×10^{-9}, 1.85×10^{-8}, and 1.04×10^{-9} $m^2.s^{-1}$, respectively [16]. However, the values found in our study did not have very similar order of magnitude of the values found in the study of Gaware et al. [16]; for example: D_{eff}(in the study of Gaware et al. [16] at 40°C) ≈ 12.85 × D_{eff} (without skin in our study at 50°C) and D_{eff}(in the study of Gaware et al. [16] at 40°C) ≈ 22.77 × D_{eff} (with skin in our study at 50°C). This difference was probably due to the non-consideration of the shrinkage phenomenon.

5. Conclusions

The main conclusions of this study can be summarized as follows:

- The drying of cherry tomato occurred mainly in a falling drying rate phase, which was divided into three sub-periods while passing by a very short adaptation phase.
- The drying rate of cherry tomato was increased by increasing the drying temperature in the range 50-70 °C**.**
- Under drying temperatures of 50, 60, 70 °C and a constant air flow and humidity, the moisture effective diffusivity ranged from 2.56×10^{-11} to 7.67×10^{-11} $m^2\cdot s^{-1}$ with activation energy of 50430 $J\cdot mol^{-1}$ in the case of tomato with skin and ranged from 4.59×10^{-10} $m^2\cdot s^{-1}$ to 6.73×10^{-10} $m^2\cdot s^{-1}$ with activation energy of 17640 $J.mol^{-1}$ in the case of tomato without skin.
- By removing the skin of cherry tomato, the drying rate was appreciably increased and the drying duration was greatly decreased.
- Removal of skin allowed drying the product at a lower temperature and this will lead to reduced consumption of energy.

In this paper, a fundamental study was presented but, nothing prevents the selection of tomatoes with a very permeable skin during a convective drying**.** In prospect, we plan to verify all these results on a pilot solar drying scale.

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