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Convective and microwave drying kinetics and modeling of tomato slices, energy consumption, and efficiency

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Abstract

This investigation presented presents the drying characteristics, and aimed to predict the drying kinetics of tomato slices (*Lycopersicon esculentum* MILL.) using convection and microwave methods. Hot air drying was carried out in a ventilated oven at 50, 60, 80, and 100°C temperatures and microwave drying was performed in domestic microwave using 300, 500, 800, and 900 W powers. Twenty-two mathematical models were undertaken to predict the drying kinetics and the best model was chosen based on the highest R^2 values and the lowest root mean square error (RMSE) and χ^2 values. Drying kinetics, drying rate variation, diffusivity and energy consumption of both methods were evaluated. Fernando and Amarasinghe model and Sledz model were the best models for convective and microwave drying processes, respectively. Effective moisture diffusivity varied from 0.28×10^{-9} to 2.81×10^{-9} and from 1.32×10^{-9} to 21.52×10^{-9}, while the activation energy was 27.64 kJ/mol and 5.71 W/g for convective and microwave drying processes, respectively. The energy consumption increases with increasing temperature or power, the reverse was observed for energy efficiency. Microwave drying process has the advantage of drying time reduction, low-energy consumption, and high-drying efficiency at a moderate high-power level (900 W). Hence, it is recommended to apply this innovative process for drying tomato slices.

KEYWORDS
convection and microwave methods, drying characteristics, Fernando and Amarasinghe model, *Lycopersicon esculentum* MILL., Sledz model

1 | INTRODUCTION

Tomato (*Lycopersicon esculentum* MILL.) from the *Salanaceae* family is native to the Andes of Peruand North Chile. It is one of the most important and commercially produced crops worldwide. It is cultivated for its richness in nutritional elements, particularly lycopene, β-carotene and it is an excellent source of vitamins (A, B1, B3, B6, and C), and minerals such as phosphorus, potassium and manganese (Azeez et al., 2019).

Tomatoes are processed into various industrial products due to their high production and very short shelf-life. Drying process is a very common processing for its transportation and storage, and the main interest in dried tomato production is its use in pestos, snacks, pizza toppings, and other savory dishes (Azeez et al., 2019; Makroo et al., 2017).

Drying is one of the oldest methods of food preservation, which consists of totally or partially removing of water from fresh materials other than their hydration water (Beşe & Polatoğlu, 2017). Moreover, it is an essential practice that allows the processing of agricultural products to facilitate their storage as well as to reduce their loss after harvesting. This process allows obtaining several dried products that represent several advantages, with new qualitative properties as well as different nutritional and economic values compared to fresh foods. Dried foods have several advantages compared to fresh foods, including reduced storage space, weight and transportation cost, fewer requirements for ease of transportation, and longer retention of nutrients and bioactive compounds (Miraei-Ashtiani et al., 2022).

Different methods are used in the drying of fruits and vegetables (Alibas, 2014) and a number of drying techniques have been developed over the years. The drying method is chosen according to the particular characteristics of the products and socio-economic considerations (Bashir et al., 2014). Connective drying process is a flexible, low cost, and an easily controlled process. These main advantages contribute to its large use. However, it could be limited by the low-thermal conductivity of some food products, since increasing temperature enhances drying rate but simultaneously leads to the degradation of some food active components (Miraei-Ashtiani et al., 2020).

Indeed, innovative methods of drying food and agricultural products such as microwave assisted drying has been developed and attracted the attention of many researchers. This method is considered to be the most economical dehydration mechanism due to the reduced loss of materials and water soluble components which means a better quality of the product, as well as reduced drying time and high-energy consumption (Abbaspour-Gilandeh et al., 2020). During microwave drying, the internal pressure of the samples reaches significant values when the internal temperature of the matrices is near the boiling point of water. The rate of drying is improved during the period of falling rate, and during this period vapors are generated inside the food materials due to volumetric heating. These vapors are forced to move outwards due to the pressure gradient, resulting in an acceleration of the drying rate. This nonuniform drying process results from the heterogeneous distribution of the microwave waves generated in the drying chamber (Miraei-Ashtiani et al., 2017).

Indeed, several studies have been carried out on the application of microwaves in industrial drying of fruits and vegetables such as kiwi slices (Darvishi et al., 2016), mango (Izli et al., 2017) and *Mytilus chilensis* and *Dosidicus gigas* (Kouhila et al., 2020) as well as plant drying: celery leaf (Mouhoubi et al., 2019) and ginger (Izli & Polat, 2019).

Thin-layer drying is the process of drying a slice of the sample; many mathematical models are used to describe this processing, since mathematical modeling is important to improve the performance of these drying systems. The models of thin-layer drying fall into three categories: empirical, semiempirical, and theoretical (Alibas, 2014).

It should be noted that several previous studies have focused on the modeling of tomato slices drying kinetics by different methods, including; solar tunnel drying (Gürlek et al., 2009; Sacilik et al., 2006), thin layer solar (Bagheri et al., 2013), infrared drying (Doymaz, 2014; Prakash & Kumar, 2014), artificial neural drying (Movagharnejad & Nikzad, 2007) and convective drying (Azeez et al., 2019). In contrast, very few studies have focused on the modeling of the kinetics of tomato slices microwave drying (Poonnoy et al., 2007; Workneh & Oke, 2013).

The study conducted by Poonnoy et al. (2007), was exclusively a modeling study using a multihidden-layer feed-forward artificial neural network of microwave-vacuum drying, they found that the two hidden layer model (25-25) was determined to be the most appropriate model. In addition, Workneh and Oke (2013) studied combined microwave-convective drying providing results on time reduction, effective diffusivities, activation energy (E_a), modeling using six models, as well as color preservation.

In view of the above and based on what it is reported in the literature, no study has yet been carried out on the comparison of two drying processes for tomato slices. The main objective of the present study was therefore to compare two drying processes; conventional (oven drying) and innovative (microwave drying) by studying their effects on the drying kinetics (drying curve and drying rate curve) and based on the evaluation of the parameters: drying time, drying rate (DR), effective moisture diffusivity (D_{eff}), specific energy consumption (SEC_e), and energy efficiency (EE). In addition, two types of modeling were applied to the drying kinetics; primary modeling using 22 models in order to design the best describing kinetics, and secondary modeling mainly for the E_a determination. All these informations are of great interest for industries since they help to design the best drying method for tomato slices, while saving energy consumption.

2 | MATERIAL AND METHODS

The tomato (*Lycopersicon esculentum* MILL.), variety Guelma 1, was bought fresh in March at the local market of Bejaia, and used the same day of its purchase, it is original from Beni Ksila region (North-West of Bejaia department, Algeria). Each tomato was chosen in a homogeneous way using three criteria: the size, the degree of ripeness (neither raw nor too ripe), and the external morphology (holy surface without cracks). Initial moisture content (MC) (94% ± 0.53% w.b $\simeq$ 16 Kg water/kg d.b) was determined on three assays according to the protocol reported by Boulekbache-Makhlouf et al. (2013). Before drying, the tomatoes were cut into a slab shape, where the average tomato thickness (0.47 ± 0.03 cm) was measured with a vernier caliper.

2.1 | Drying equipment and drying procedure

Drying of tomatoes was carried out by two methods namely hot air drying and microwave drying (Figure 1). Hot air drying was carried out in a conventional oven dryer (Memmert Model UFB 400, with air circulation, GmbH + Co. KG, Germany); the oven has the following technical features: 230 V, 6.1 A, 50/60 Hz, 1400 W. It has the ability to regulate the temperature in the range of 20–220°C. Microwave drying treatment was achieved in a domestic digital microwave oven (Maxipower, Model MASMO23S, China), having the following technical features: 230 V/50 Hz, and 1400 W, its operation frequency is

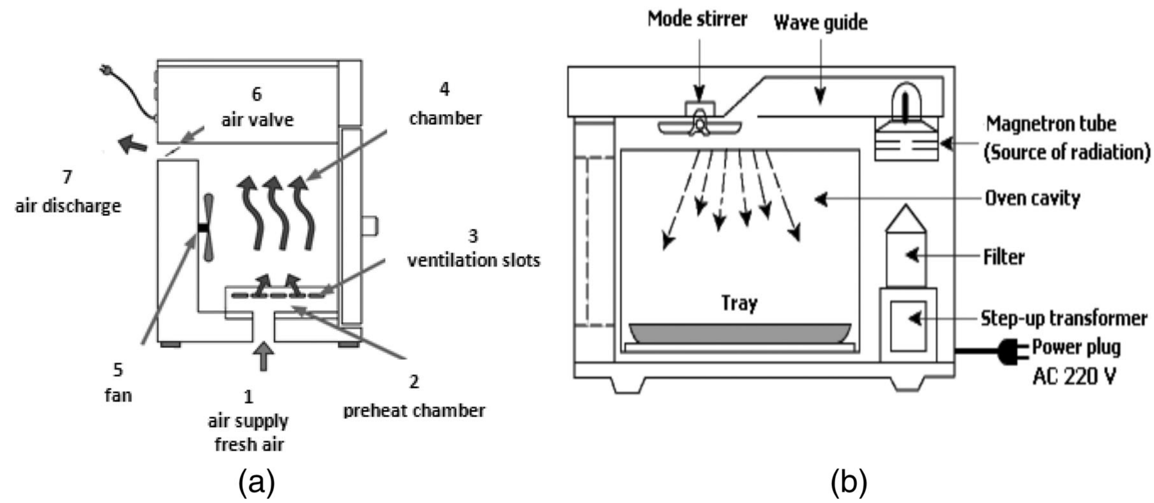

FIGURE 1 Schematic of the dryers: (a) conventional oven and (b) microwave oven. (Mouhoubi, et al., 2022)

equal to 2450 MHz. The microwave oven capacity dimension is 220 (H) × 340 (W) × 320 (D) mm^3, and it has a glass plateswiveling at the right and the left. A digital control system for irradiation time and microwave power is also provided within the apparatus, it was linearly adjustable from 100 to 1000 W. Drying experiments were conducted at different temperatures of 50, 60, 80, and 100°C and at different microwave powers that were equal to 300, 500, 800, and 900 W.

During this drying process, 200 g of tomato slices were uniformly spread in a monolayer and moisture losses were periodically measured with an external analytical accuracy of 0.01 g (RADWAG, WPS 600/C/2, Poland). Three tests were carried out for each temperature and power, and the recorded data were the mean of these results. The drying process was applied to the samples until the weight of each assay was stabilized.

2.2 | Mathematical modeling

Various mathematical models were reported to study the modeling of thin-layer drying kinetics of tomato (Azeez et al., 2019). For this purpose, experimental data of reduced *MC* obtained at adopted temperatures and drying powers were simulated by twenty-two (22) different drying models as shown in Table 1.

Absolute moisture is defined as the ratio between *MC* and dry matter, it is determined for each experimental data. Table 1 is composed of 22 mathematical equations that are frequently used to adapt empirical correlations describing the drying behavior of natural products. These equations, which express the moisture ratio (*MR*) as a function of time (*t*), were used to convert the drying curves of tomato slices. The determination of the *MR* is defined generally as given in Equation 1.

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

where *MR* is the moisture ratio; M_t, M_o, and M_e designate the *MC* at any point in the drying process, the initial *MC* and the equilibrium *MC* (kg water/kg dry matter), respectively. M_e values are relatively low compared to M_t or M_o (Aghbashlo et al., 2009).

Thus, the *MR* can be calculated as follows:

$$MR = M_t / M_0. \tag{2}$$

2.3 | Drying rate

Graphical drawings of the *DR* versus time allow us to determine the drying behavior (Aral & Beşe, 2016; Beşe & Polatoğlu, 2017). This parameter can be calculated by the following equation:

$$DR = \frac{M_{t+dt} - M_t}{dt}, \tag{3}$$

where *DR* is the drying rate (kg H_2O/kg dry matter), M_{t+dt} is the *MC* at $t + \Delta t$ (kg H_2O/kg dry matter), M_t is the *MC* at *t* (kg H_2O/kg dry matter), and *dt* is the difference in drying time (min).

2.4 | Determination of D_{eff}

Water migrates from the interior to the surface of the product through a variety of mechanisms that can be combined. In this analysis, the main mechanism of water transport for tomato slices is considered to be a diffusive mechanism; this D_{eff}, is generally accepted as an important kinetic parameter calculated by Fick's second law. This law has been widely used to describe the moisture transport of material in unstable state (Aral & Beşe, 2016; Crank, 1979):

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{\left(\frac{(2n+1)^2 \pi^2}{4L^2} D_{eff} t\right)} \tag{4}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), *L* is the half-thickness (drying on both sides) of the tomato slices ($L = 0.00468$ m), *n* is the positive integer and *t* is the drying time (s).

TABLE 1 Mathematical models given by various authors for drying curves

Name	Mathematical equation	References
Newton	$MR = exp(-kt)$	(Mouhoubi et al., 2019)
Henderson and Pabis	$MR = a.exp(-kt)$	(Nema et al., 2013)
Logarithmic	$MR = a.exp(-kt) + c$	(Nema et al., 2013)
Page	$MR = exp(-kt^n)$	(Nema et al., 2013)
Modified page 1	$MR = exp(-[kt]^n)$	(Nema et al., 2013)
Modified page 2	$MR = exp(-kt)^n$	(Mouhoubi et al., 2019)
Midilli et al.	$MR = a.exp(-kt^n) + bt$	(Nema et al., 2013)
Two terms	$MR = a.exp(-kt) + b.exp(-k_1\, t)$	(Nema et al., 2013)
Two terms exponential	$MR = a.exp(-kt) + (1-a).exp(-kat)$	(Nema et al., 2013)
Approximation of diffusion	$MR = a.exp(-kt) + (1-a).exp(-kbt)$	(Nema et al., 2013)
Verma et al.	$MR = a.exp(-kt) + (1-a).exp(-k_1 t)$	(Nema et al., 2013)
Modified Henderson and Pabis	$MR = a.exp(-kt) + b.exp(-k_1 t) + c.exp(-k_2 t)$	(Mouhoubi et al., 2019)
Parabolic	$MR = a + b.t + c.t^2$	(Dinani et al., 2014)
Wang and Singh	$MR = 1 + a.t + b.t^2$	(Nema et al., 2013)
Chavez-Mendez et al.	$MR = (1-[l-L_2]L1t)^{l/(l-L_2)}$	(Nema et al., 2013)
Logistic	$MR = b/(1 + a.exp[k.t])$	(Sledz et al., 2016)
Sledz et al.	$MR = b.exp(-k.t)/(1 + a.exp[k_1.t])$	(Sledz et al., 2016)
Simplified Fick's diffusion equation	$MR = a.exp(-k[t/L_2])$	(Aghbashlo et al., 2009)
Weibull	$MR = exp(-t/a)^b)$	(Mouhoubi et al., 2019)
Demir et al.	$MR = a.exp(-kt)^n + b$	(Mouhoubi et al., 2019)
Taghian Dinani et al.	$MR = a.exp(-([t-b]/a)^2)$	(Dinani et al., 2014)
Fernando and Amarasinghe	$MR = (1 + a.t + b.t^2)/(1 + c.t)$	(Fernando & Amarasinghe, 2016)

Note: k, k_1, k_2 - drying coefficients (1/min); a, b, c, L_1, L_2 - coefficients of the equations; n- exponent; t - time (min); L - half of thickness (m).

For a sufficiently long drying time, only the first term of Equation (4) should be used, as the second and third terms are not significant and can therefore be simplified in logarithmic form according to the following equation (Kouhila et al., 2020):

$$\ln(MR) = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2}, \tag{5}$$

Equation (5) is evaluated numerically for Fourier number, $F_0 = D_{eff} \cdot t/4L^2$ (Darvishi et al., 2014), and this last equation can be rewritten as follows:

$$\ln(MR) = \ln\frac{8}{\pi^2} - \pi^2 F_0, \tag{6}$$

with:

$$F_0 = -0.101\ln(MR) - 0.0213, \tag{7}$$

Then the D_{eff} will be calculated according to Equation (8):

$$D_{eff} = \frac{F_0}{\left(\frac{t}{4L^2}\right)} = \frac{-0.101\ln(MR) - 0.0213}{\left(\frac{t}{4L^2}\right)}. \tag{8}$$

2.5 | Activation energy

E_a is the amount of energy required to remove moisture from a solid matrix (Aghbashlo et al., 2009), for which the Arrhenius equation has been represented to study the effect of temperature (Mouhoubi et al., 2019). In the case of hot air assisted drying, the relationship between temperature and D_{eff} was used by calculating the E_a according to Equation (9) (Darvishi et al., 2014):

$$D_{eff} = D_0 e^{\left(\frac{-E_a}{RT}\right)}, \tag{9}$$

However, in the case of microwave-assisted drying, the E_a has been modified from the Arrhenius equation, it is assumed that this energy is related to the speed of the drying kinetics and the ratio of microwave power to sample weight (m/P), rather than to air temperature, so Equation (9) can be represented as follows Equation (10) (Darvishi et al., 2014).:

$$D_{eff} = D_0{}' e^{\left(\frac{-E_a m}{P}\right)}, \tag{10}$$

where D_{eff} is the effective diffusivity (m^2/s), D_0 and D_0' are the pre-exponential factors (m^2/s) in oven and microwave, respectively, R is the universal gas constant (8.314 kJ/mol K), T is the temperature (K), m is the mass of raw sample (g), P is the power (W), and E is the E_a expressed in (kJ/mol) for hot air drying and in (W/g) for microwave drying.

2.6 | Energy consumption

Energy consumption during our drying work can be calculated using two different efficiency indices, the specific electric energy consumption according to Equation (11) and the EE according to Equation (12) (Tsotsas & Mujumdar, 2014):

$$SEC_e = \frac{3600E}{M_s(X_i - X_f)}, \tag{11}$$

where SEC_e is the specific electric energy consumption (MJ/kg of water), E is the total electric energy consumption (kWh), X_i and X_f show the initial and final *MC*s (d.b), respectively, and M_s is the mass of dry solid matter (kg).

$$EE = M_s(X_i - X_f)\frac{\Delta h_v}{3600E}.100, \tag{12}$$

where *EE* is the electrical energy in (%) and Δhv is the enthalpy of evaporation of water (2257 kJ/kg, at 100°C).

2.7 | Statistical analysis

For the modeling of the drying kinetics, a nonlinear regression analysis was performed using STATISTICA software 8.0 (StatSoft Inc., USA). Three statistical parameters were used to determine the ability of the tested mathematical model store present the experimental data, namely: the determination coefficient (R^2), the chi-square (χ^2), and the RMSE. According to Abbaspour-Gilandeh et al. (2020). For a better fit, the best mathematical model should have the highest R^2 value and the lowest (χ^2) and (*RMSE*) values. These parameters are calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{N - z}, \tag{13}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{N}}, \tag{14}$$

where $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental *MR* and predicted *MR*, respectively; *N* is the number of observations and is the number of parameters.

The differences between D_{eff}, SEC_e, and *EE* values were tested by the JMP software 7.0.0 (SAS Institute Inc., Cary, NC, USA). The meaning of the differences between these values has been defined by the Tukey test at $p \leq .05$.

3 | RESULTS AND DISCUSSION

3.1 | Drying curves

As shown in Figure 2a,b, the *MR* of tomato samples decreases as the drying time decreases whether in the oven or in the microwave. These kinetics are characterized by a rapid decline in the *MC* at the beginning of the drying process. This is due to the high diffusion of water during the drying process, which induces a diminution in absorption because of the reduction of the water content in the product to be dried (Alibas & Kacar, 2016).

It is also noted that oven temperature and microwave power levels have a significant effect on *MC*. Indeed, it is clear from the curves that the decrease in *MC* becomes faster as the temperature and power levels increase. For example, the drying time required to reach the lowest *MC* has been reduced from 780 to 140 min for temperatures ranging from 50 to 100°C. The times recorded after drying at 80 and 60°C were 245 and 170 min, respectively. Regarding power levels, the times varied from 89.5 to 4.58 min for power levels ranging from 300 to 900 W. Drying process at 800 and 500 W powers recorded times of 5.92 and 7.92 min, respectively.

These findings showed clearly that an increase in temperature or power levels leads to a reduction in drying time, which agrees with study conducted on cherry tomato drying (Kipcak & Doymaz, 2019). Furthermore, the results of this study are in agreement with those of previous investigations on convection drying (İzli, 2017; Izli & Polat, 2019; Nguyen et al., 2015), and microwave drying (Abbaspour-Gilandeh et al., 2020; Alibas et al., 2019; Darvishi et al., 2016; Izli & Polat, 2019) of different food products other than tomatoes.

Furthermore, the comparison of the two drying processes, convective and microwave, in terms of reduction of drying times, leads to the most remarkable observation that microwaves are much more efficient for drying tomato slices than convective drying. Such a result is consistent with several recent studies conducted on different matrices (Ali et al., 2020; Alibas et al., 2021; Mouhoubi et al., 2022).

The possible explanation for such an observation is that, microwave targets the microscopic moisture inside the plant material directly, thereby increasing the internal temperature via volumetric heating and leading to faster evaporation (Ali et al., 2020). During microwave drying process as soon as the inner temperature of food materials becomes closer to the water boiling point, the intern material pressure reaches important levels. The increase in vapor pressure allows water migration to material surfaces leading to a faster *DR* in comparison with convective drying in which heat moves from the surface to the inner parts of materials. Nevertheless, in microwave drying there is a nonuniform distribution of waves within the drying compartment, leading consequently to a nonuniform drying. Additionally, in microwave drying the evaporated water is not transferred from the product surface, so air movement is required in this type of drying process. Since cold aeration has a low-water absorption ability, warm air could be more economic (Miraei-Ashtiani et al., 2018).

3.2 | Modeling of the experimental data

Mathematical modeling of the drying process is an important aspect in drying technology without postharvest treatment of agricultural materials (Harish et al., 2014). It is important to make mathematical modeling of drying kinetics in order to incorporate experimental research data of food drying into industrial applications (Miraei-Ashtiani et al., 2017). Several models have been found in the literature but new ones have been proposed by other authors (Dinani et al., 2014; Fernando & Amarasinghe, 2016; Sledz et al., 2016).

Various mathematical models have been reported to study the modeling of thin-layer drying kinetics of tomato. In order to better

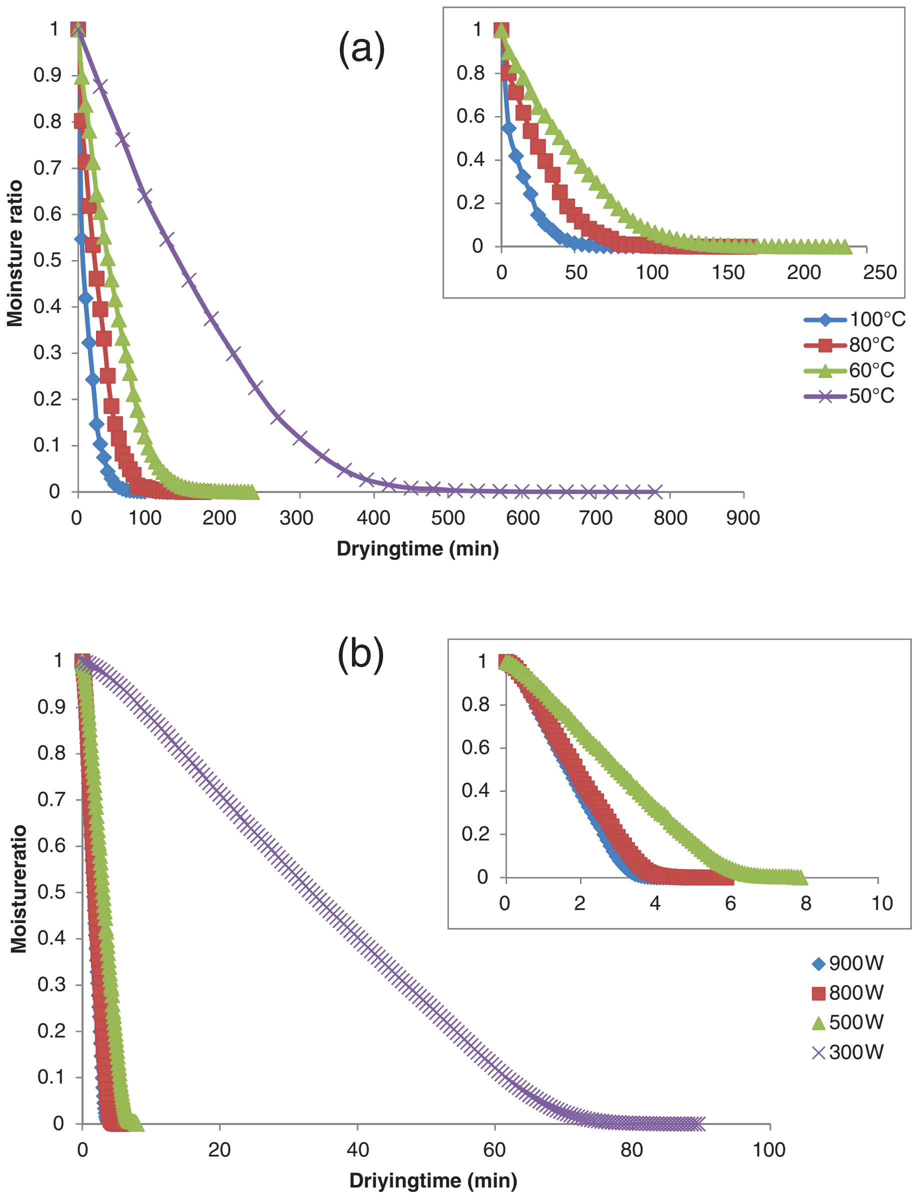

FIGURE 2 Moisture ratio profiles of tomato slice during convective drying at various temperatures (a) and microwave drying at various power levels (b)

assess the model that interprets these kinetics, 22 mathematical models (Table 1) were tested and the best ones were selected based on the following parameters: coefficient of determination (R^2), Chis-quare (χ^2) and *RMSE*.

According to the results related to the behavior of the tomato slices during drying, 4 best models were chosen among the 22 treated ones for each drying method (microwave and conventional method). In fact, these models confirmed the quality of the fit with the highest R^2 values and the lowest χ^2 and *RMSE* values (Tables 2 and 3).

For temperatures, the requiered parameters were given by the Fernando and Amarasinghe model, with $0.9943 \le R^2 \le 0.9976$, $0.000261 \le \chi 2 \le 0.000383$, and $0.015100 \le RMSE \le 0.017491$. Concerning powers, the adequate R^2, χ^2, and *RMSE* values were recorded in the Sledz model, with $0.9971 \le R^2 \le 0.9988$, $0.000135 \le \chi 2 \le 0.000393$, and $0.011471 \le RMSE \le 0.018021$. Therefore, both models were chosen as the optimal models for their satisfactory descriptions of tomato slice drying. Equivalent patterns have been already revealed in other studies but the suitable models may differ depending on the applied procedure and the used matrix as established by Izli et al. (2017) and İzli (2017) for mango and date drying, respectively.

It should be noted that the Sledz model proved to be the best model for drying several matrices such as parsley (Sledz et al., 2016), basil (Sledz et al., 2017), and celery (Mouhoubi et al., 2019), while Fernando and Amarasinghe model was adopted for drying coconut pith (Fernando & Amarasinghe, 2016).

3.3 | Effective moisture diffusivity

The effective diffusivity (D_{eff}) was calculated using Equation (8), and the values are shown in Table 4. As indicated, the D_{eff} increases with

TABLE 2 The values of drying constants and coefficients and the statistical paramaters of the best models for all the drying temperatures

Models	T (°C)	The drying constants and coefficients				Statistical parameters		
Fernando and Amarasinghe		*a*	*b*	*c*		R^2	χ^2	RMSE
	50°C	−0.003791	0.000003	0.000977		0.9976	0.000261	0.015100
	60°C	−0.011709	0.000033	0.005080		0.9967	0.000284	0.016312
	80°C	−0.017912	0.000077	0.015143		0.9959	0.000338	0.017491
	100°C	−0.022587	0.000121	0.095226		0.9943	0.000321	0.016882
Taghian Dinani et al.		*a*	*b*	*c*		R^2	χ^2	RMSE
	50°C	1.139586	−0.439	1.2147		0.9952	0.123680	0.328969
	60°C	1.279624	−48.8009	91.76071		0.9986	0.000125	0.010804
	80°C	1.791315	−50.9304	64.48140		0.9974	0.000217	0.014016
	100°C	236.255799	−153.3979	65.221315		0.9864	0.000763	0.026039
Sledz et al.		*b*	*k*	*a*	k_1	R^2	χ^2	RMSE
	50°C	62.06119	0.01921	60.78903	−0.01481	0.9999	0.000010	0.002840
	60°C	1.065876	0.021707	0.000000	0.090706	0.9832	0.001496	0.036995
	80°C	0.303729	0.036145	−0.701919	0.000001	0.9900	0.000845	0.027196
	100°C	0.408194	0.086463	−0.570719	0.005499	0.9891	0.000638	0.023306
Logistic		*k*	*a*	*b*		R^2	χ^2	RMSE
	50°C	0.010913	0.401364	1.374455		0.9982	0.000195	0.013050
	60°C	0.034524	0.430814	1.366037		0.9976	0.000207	0.013921
	80°C	0.051641	0.754583	1.672434		0.9963	0.000300	0.016489
	100°C	0.1	497,268.5	471,439.1		0.9887	0.000634	0.023735

TABLE 3 The values of drying constants and coefficients and the statistical paramaters of the best models for all microwave power levels

	P (W)	The drying constants and coefficients				Statistical parameters		
Parabolic		*a*	*b*	*c*		R^2	χ^2	RMSE
	300 W	1.068509	−0.020391	0.000085		0.9945	0.000615	0.024654
	500 W	0.885951	−0.006634	0.000012		0.9833	0.001931	0.043249
	800 W	1.111022	−0.416443	0.038198		0.9908	0.001159	0.033310
	900 W	1.087892	−0.408172	0.031287		0.9915	0.000000	0.000000
Logistic		*k*	*a*	*b*		R^2	χ^2	RMSE
	300 W	0.069007	0.119321	1.090100		0.9937	0.000708	0.026377
	500 W	0.011926	30.525217	29.912832		0.9956	0.000504	0.022093
	800 W	1.307521	0.104085	1.090304		0.9959	0.000514	0.022182
	900 W	1.491205	0.092862	1.080105		0.9944	0.000712	0.025889
Fernando and Amarasinghe		*a*	*b*	*c*		R^2	χ^2	RMSE
	300 W	−0.025283	0.000159	−0.009916		0.9977	0.000256	0.016005
	500 W	−0.003706	0.000002	0.011732		0.9953	0.000547	0.023022
	800 W	−0.413905	0.042214	−0.122332		0.9907	0.001167	0.033415
	900 W	−0.520926	0.067561	−0.219843		0.9929	0.000899	0.029087
Sledz et al.		*b*	*k*	*a*	K_1	R^2	χ^2	RMSE
	300 W	476.0962	0.1322	455.1592	−0.1136	0.9988	0.000135	0.011471
	500 W	0.922190	0.011296	−0.077803	−0.329558	0.9971	0.000339	0.018021
	800 W	179.1381	2.1360	170.5173	−1.8441	0.9986	0.000174	0.012811
	900 W	250.6111	2.5101	238.2961	−2.1882	0.9982	0.000238	0.014798

TABLE 4 Result of SEC_e, EE calculation and effective diffusivity for tomato slices at different temperatures and microwave powers

T (°C)	Convection drying			P (W)	Microwave drying		
50°C	SEC_e ($\times 10^{-6}$ MJ/kg H2O)	EE ($\times 10^{-2}$%)	Diffusivities ($\times 10^{-9}$ m^2/s)	300 W	SECe ($\times 10^{-6}$MJ/kg H2O)	EE ($\times 10^{-2}$%)	Diffusivities ($\times 10^{-9}$ m^2/s)
	30.29 ± 0.9^{aA}	0.77 ± 0.02^{dD}	0.28 ± 0.01^{dC}		2.91 ± 0.12^{aD}	7.75 ± 31.9^{dD}	1.32 ± 0.13^{cC}
60°C	9.39 ± 0.06^{bB}	2.53 ± 0.02^{cD}	0.81 ± 0,05^{cC}	500 W	0.29 ± 0.03^{bE}	77.03 ± 8.98^{cC}	7.92 ± 0.77^{bB}
80°C	6.45 ± 0.17^{cC}	3.69 ± 0.99^{bD}	1.53 ± 0.08^{bC}	800 W	0.19 ± 0.001^{bE}	116 ± 1^{bB}	21.15 ± 0.74^{aA}
100°C	5.35 ± 0.57^{cC}	4.48 ± 0.48^{aD}	2.81 ± 0.27^{aC}	900 W	0.15 ± 0.002^{bE}	146.97 ± 1.71^{aA}	21.52 ± 2.28^{aA}

Note: Table shows mean values with SD of the mean. [a,b]Same index letters indicate that the mean values are not significantly different at a confidence level of 95% ($p \leq .05$)for the same process. [A,B]Same index letters indicate that the mean values are not significantly different at a confidence level of 95% ($p \leq .05$) between the two process.

increasing drying temperature and power, a proportional relationship was noted between this parameter and the used temperature and power.

In fact, for oven, drying the values ranged between 0.28×10^{-9} and 2.81×10^{-9} m^2/s when varying temperatures from 50 to 100°C, whereas for microwave drying the results varied between 1.32×10^{-9} and 21.52×10^{-9} m^2/s as the powers passed from 300 to 900 W.

The obtained D_{eff} values are therefore within the general range of 10–12 to 10–8 m^2/s defined for food products (Kaveh, Karami, & Jahanbakhshi, 2020) and are in good agreement with the values published by other researchers (Boateng et al., 2021; Kaveh, Golpour, et al., 2021; Taghinezhad et al., 2020).

The calculated D_{eff} values of tomato slices are consistent with the values given in the literature by Abano et al. (2012), who found results between 7.22×10^{-9} and 25.19×10^{-9} m^2/s for combined microwave-vacuum drying, and Giovanelli et al. (2002) whose results are 2.3–9.1 $\times 10^{-9}$ m^2/s for oven drying from 60 to 110°C. Bagheri et al. (2013) estimated results between 3.42×10^{-9} and 8.69×10^{-9} m^2/s using full sun drying. The differences between these results can be explained by the effect of the type, shape, size and initial and final moisture of the cultivated matrix as well as the thickness of the cut slice, the composition and characteristics of the tomato tissues and the proposed model used for the calculations (Miraei-Ashtiani et al., 2020).

Regarding microwave drying, a porous structure is formed, simultaneously moisture transfer can take place in the form of vapor and thus the product temperature rises rapidly in the early stages of drying. Substantial microwave heat absorption allows the product to have a high-loss factor at higher *MC*. This increases the water vapor pressure inside the pores and induces their opening (Darvishi et al., 2016; Mouhoubi et al., 2019).

The same drying process showed that there was a significant difference between the obtained D_{eff} values for all studied temperatures (40, 60, 80, and 100°C). However, in the case of microwave drying, significant differences were only observed when low-power levels (300 and 500 W) were applied. Nevertheless, the value obtained at 800 W is not statistically different from that obtained at 900 W.

The D_{eff} results for both drying techniques exposed that the values found in convective drying, or even at all temperatures (40, 60, 80, and 100°C) are not statistically different from those obtained at 300 W. The other powers (500, 800 and 900 W) have a statistically different values compared to the results of convective drying.

3.4 | *DR* versus *MC*

A correlative relationship between the *DR* and the *MC* can be seen in Figure 3a,b. In fact, in convective drying the highest *DRs* were perceived when the *MC* of the tomato slices is higher, then they decrease when the *MC* of the slices is lower. The likely explanation for this is that during the first stage of this period, water is removed from the large capillaries and then from the small capillaries, leading to a reduction in the rate of evaporation, while the latter part of the process corresponds to the removal of water that is strongly bound to the sites of the water-holding ingredients, and thus water extraction becomes more difficult and the rate of drying decreases (Boateng et al., 2021).

In microwave drying, periods of constant *DR* were detected under low power drying conditions, followed by a decrease as the *MC* of the tomato slices decreased. On the other hand, in the case of extremely high powers (800 and 900 W), there was no constant drying period, but rather a significant rise in the *DR* which then dropped continuously. These observations are explained by the fact that, the *MC* of the samples was very high during the initial phase of drying, which resulted in higher absorption of microwave power and higher drying rates due to higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of microwave power and resulted in a decrease in the drying rate (Altay et al., 2019).

Generally, regardless of the *MC* of the tomato slices, it is the highest temperature or power level that marks the highest *DR*, for example: at a temperature of 50°C, the average *DR* was about 0.02 kg water/kg dm min, while at the highest temperature (100°C) it reached the value of 0.12 kg water/kg dm min. Similarly, the average *DR* at the lowest power (300 W) was 0.19 kg water/kg dm min and 3.73 kg water/kg dm min at the highest power (900 W). Similar trends have been observed and reported in the literature for convection and microwave drying by several authors (Alibas et al., 2019; Alibas & Yilmaz, 2021; Aral & Beşe, 2016; Boateng et al., 2021; Kouhila et al., 2020).

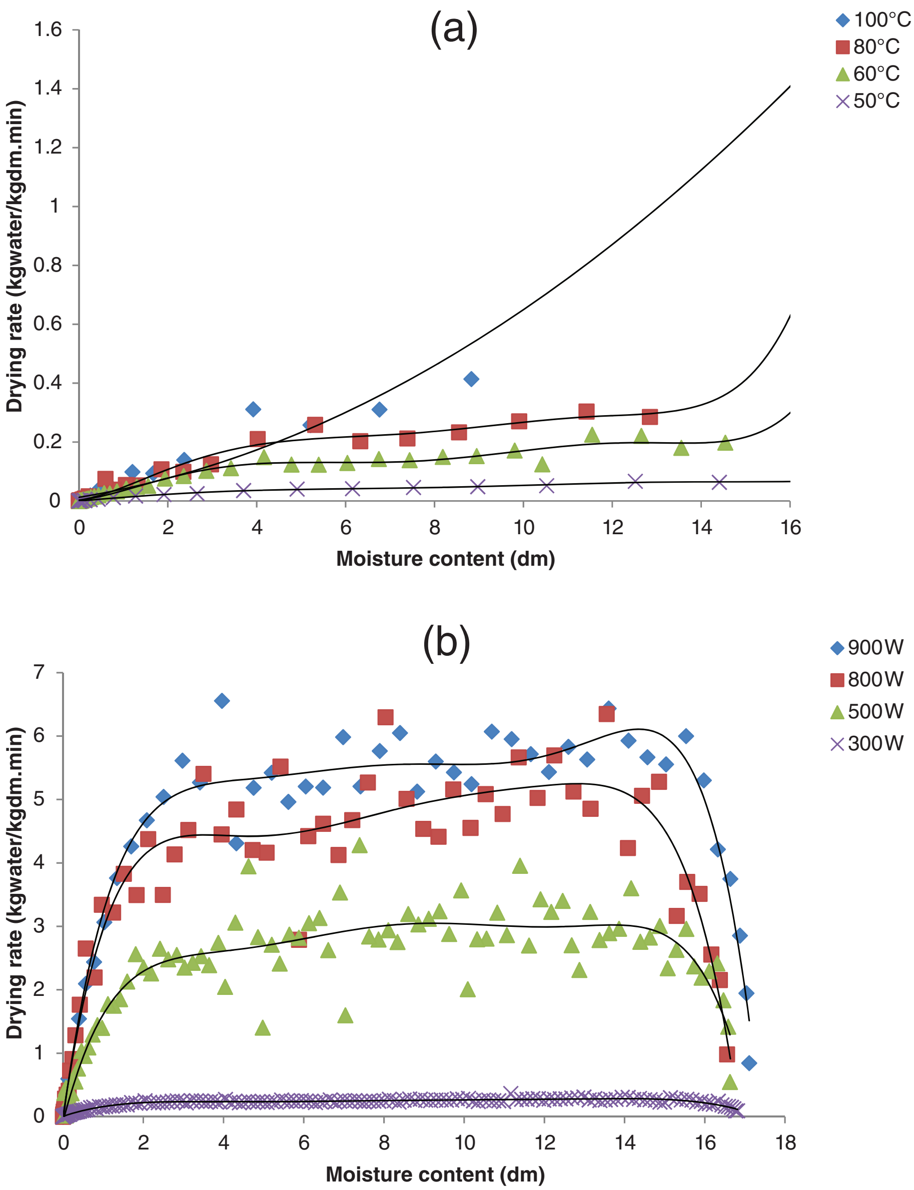

FIGURE 3 Variation of drying rate as function of moisture content at different temperatures of hot air drying (a) and at different microwave powers (b)

Furthermore, the comparison of both drying processes, convective and microwave, in terms of drying rate, leads to the conclusion that microwave is much more efficient than convective drying. In the literature, other researchers have also stated that microwave power has an accelerating effect on the drying rate (Altay et al., 2019; Mouhoubi et al., 2019; Mouhoubi, et al., 2022; Yilmaz & Alibas, 2021).

3.5 | Activation energy

The E_a of both drying methods were calculated by Equations 9 and 10. The acquired values were 27.64 KJ/mol and 5.71 W/g for oven and microwave drying methods, respectively.

According to Mortaza Aghbashlo et al. (2008), the value of E_a represents the energy required to initiate the mass transfer of the product. If the *MC* is absorbed by the surface, it requires less energy to cause evaporation. Therefore, the obtained E_a values in this study were within the recommended range (12.7–110 kJ/mol) for agricultural products (Aral & Beşe, 2016; Samimi-Akhijahani & Arabhosseini, 2018). Besides, they are comparable to the results given in the literature even though drying conditions are different. For example, for pumpkin seeds dried at temperatures between 50 and 80°C, values of 31.94 and 34.49 kJ/mol were obtained (Chayjan et al., 2013), and for nectarine slices dried at temperatures between 50 and 70°C, the following values were reported: 31.28 and 35.23 kJ/mol (Alaei & Chayjan, 2015).

Doymaz and İsmail (2011) established a value of 43.05–49.17 kJ/mol for sweet cherry dried at 60–75°C. The same researchers identified a E_a value of 22.7–23.2 kJ/mol for sweet potato slices dehydrated at 50–70°C. Chayjan et al. (2013), whom studied pumpkin seeds at temperatures between 50 and 80°C, determined a value of 31.94 and 34.49 kJ/mol. Alaei and Chayjan (2015) recorded a values of 31.28 and 35.23 kJ/mol when studying nectarine slices at temperatures between 50 and 70°C and the E_a noticed by Aral and Beşe

(2016) for hawthorn were 78.74 and 91.54 kJ/mol. Coşkun et al. (2017) reported a value of 12.43 kJ/mol for tomatoes and a result ranging from 27.6 to 45.3 kJ/mol for melon seeds.

These values are also equivalent to those estimated by Mouhoubi et al. (2019) for celery leaves (36.09 kJ/mol), and Azeez et al. (2019) for tomato slices dried at 50–70°C (31.19 kJ/mol). More recently, Abbaspour-Gilandeh et al. (2020) detected a E_a of 33.06 to 34.77 kJ/mol for quince.

Nevertheless, the E_a values noted for microwave-assisted drying are different from those reported in the literature. Özbek and Dadali (2007), obtained a result of 12.284 W/g for mint leaves. For drying pepper, a E_a of 14.67 was noted by Darvishi et al. (2014), and for kiwi slices a values between 17.96 and 21.38 W/g were observed (Darvishi et al., 2016). Recently, the E_a of 77.3 W/g was determined for celery leaves drying (Mouhoubi et al., 2019).

However, comparatively to the results found in this study, low E_a of 5.54, 3.986, and 9.361 W/g were also reported for okra (Dadalı et al., 2007), white mulberry (Darvishi, Zarein, et al., 2014), and *Mytilus Chilensis* (Kouhila et al., 2020), respectively.

3.6 | Energy consumption and *EE*

The results for SEC_e and *EE* are presented in Table 4. These two parameters showed an inversely proportional relationship. Indeed, SEC_e decreases as power and temperature increase, in fact, SEC_e values vary from 30.29×10^{-6} to 5.35×10^{-6} MJ/kg for convection drying and from 0.15×10^{-6} to 0.48×10^{-6} MJ/kg for microwave drying, while *EE* values increased from 0.77×10^{-2} to 4.48×10^{-2}% when temperatures fluctuated between 50 and 100°C, and from 46.5×10^{-2} to 146.97×10^{-2}% for power levels ranging from 300 to 900 W. It should be noted that such an opposite relationship observed for SEC_e and *EE* has also been noted by many researchers: Tsotsas and Mujumdar (2014), Mouhoubi et al. (2019), Maftoonazad et al. (2020), Kaveh, Abbaspour-Gilandeh, and Nowacka (2021) and Mouhoubi et al. (2022).

The decrease in SEC_e values has already been reported by many authors (EL-Mesery, Kamel, & Emara, 2021; Mouhoubi et al., 2019).

The possible explanation for the decrease in SEC_e during convective drying, is that when increasing the temperature, the thermal gradient and the acceleration of moisture extraction were improved which implies a reduction in drying time and SEC_e (Kaveh, Amiri Chayjan, et al., 2020). As for its decrease during microwave drying, this is explained by the fact that the very efficient diffusion of moisture when using high-power microwaves, due to the changes in cell structure, leads to faster release of moisture and reduction of drying time, and thus a reduction in energy consumption (Jahanbakhshi et al., 2020).

Statistical analysis revealed the existence of significant differences for both SEC_e and *EE* values, but the most remarkable observation was that SEC_e (highest SEC_e values) was attributed to conventional drying, while *EE* (highest *EE* values) was attributed to microwave assisted drying.

4 | CONCLUSION

In this research, a comparative study of the drying behavior of tomato slices using two methods; convective and microwave was investigated. The results stated that:

- Drying time was relatively high during convective drying compared to microwave drying (140 min at 100°C vs. 4.58 min at 900 W).
- The drying times found in this study are largely explained by the variation in *DRs*, as they show an inverse trend with time.
- Maximum and minimum D_{eff} values were calculated: 21.52 ± 2.28×10^{-9} m^2/s (microwave at 900 W) and 0.28 ± 0.01×10^{-9} m^2/s (convective at 50°C).
- Among the 22 models used to predict the *MR* of tomato slices, the Fernando and Amarasinghe model and the Sledz model were proven to be the best models describing the oven and microwave drying characteristics, respectively.
- The highest energy consumption (30.29 ± 0.9×10^{-6} MJ/kg H_2O) was recorded when applying convective drying.
- The highest *EE* in drying was achieved for microwave drying (146.97 ± 1.71% at 900 W).

Overall, it can be deduced that microwave assisted drying is the best technique for drying tomato slices, based on the determined characteristics, such as shorter drying time, high-drying rates, high diffusivity, low-energy consumption and high-drying efficiency.

Nevertheless, it will be desirable, during the next research works, to evaluate the effect of the various drying processes under their different conditions on the quality of the dried powders, in particular by the evaluation of the color, the determination of the polyphenol content, their antioxidant activity and their characterization and the determination of pigments (carotenoids, lycopene, …).

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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