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Influence of convective and microwave drying on Algerian blood orange slices: Drying kinetics and characteristics, modeling, and drying energetics

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Abstract

This research work aims to explore for the first time the effect of two drying processes on Algerian blood oranges (*Citrus sinensis* [L.] Osbeck): microwave (200, 400, 600, and 800 W) and convective (40°C, 60°C, 80°C, 100°C, and 120°C), on drying characteristics. The drying time was reduced from 90 min at 120°C (rate of 2.00×10^{-2} kgH₂O/kg dm.min) to 13 min at 800 W microwave output (rate of 28.86×10^{-2} kgH₂O/kg dm.min). The drying data were fitted to 38 models. Sledz et al. and Midilli and Kucuk models were found to be the best fit to describe drying kinetics for microwave and convective, respectively. The effective diffusivity ranged from 2.07×10^{-9} to 15.67×10^{-9} m²/s for microwave and from 0.07×10^{-9} to 1.97×10^{-9} m²/s for convective drying. The activation energy was estimated to be 8.871 W/g and 33.7 kJ/mol for microwave and convective respectively. The highest energy consumption was obtained by convective drying (0.49×10^7 MJ/kgH₂O) whereas the highest energy yield was obtained by microwave drying ($36.93 \times 10^{-2}\%$).

Practical Applications

Due to the great variability of drying techniques, it is difficult to design the best process for a given product. When choosing a process, several parameters must be considered including precise process control, short drying time, low energy consumption, and high energy efficiency. Blood orange is a seasonal variety, to make it available, drying is one of the most used techniques. Thus, the objective of this study was to compare two drying processes of blood orange slices (microwave, convective). The results of this research allowed to select an alternative technique (microwave) to

manufacture dehydrated orange slices that could be useful to facilitate their use out off-season in the formulation of different food products, food fortification, and pharmaceutical industry.

Novelty Impact Statement: Two conventional and innovative drying methods were applied to dry blood orange slices, and in terms of kinetic results and modeling. The models of Midilli and Kucuk and Sledz were best suited for convective and microwave drying, respectively. Microwaves provide faster drying, low energy consumption, and high energy efficiency.

KEYWORDS

Citrus sinensis [L.] Osbeck, drying kinetics, energy consumption, energy efficiency, kinetic parameters, modeling

1 | INTRODUCTION

Citrus represents a large part of the world's fruit tree crop, with more than 129 million tons in 2018, of which oranges account for about 58.4% of the total production, followed by mandarins with about 26.6%. Lemons and limes are the third most essential citrus species, with 15% of the total produced (Bechlin et al., 2020). There are two clearly differentiated markets: the fresh fruit market and the processed juice market (Ollitrault et al., 2012). In recent years, the consumption of fresh product has decreased, while the market for natural, healthy, and tasty products is increasing, not only for end-products, but also as ingredients to be included in complex foods such as cereals, ice cream, dairy products, confectionery, and bakery products (Diaz et al., 2003).

The drying process offers many benefits for food preservation, reduced packaging and transportation costs, and reduced weight and volume (logistics). In addition, the drying process reduces the moisture content to a level where no microbiological growth can occur while maintaining higher nutritional values (Hnin et al., 2021; Kouhila et al., 2020).

The food industry primarily uses traditional hot air convection drying because of its low operating cost and ease of control. However, hot air drying adversely affects key aspects of food safety, namely nutritional quality and environmental sustainability. Prolonged heat treatment of foods adversely affects organoleptic characteristics and bioactive substances (Miraei Ashtiani et al., 2022). Therefore, new drying methods are needed to reduce energy consumption and improve product quality (Miraei Ashtiani et al., 2020).

Microwave technology is widely used in the drying process according to rapid heat transfer, volumetric heating, non-polluting, and selective (Liu, Wang, et al., 2020; Mouhoubi, Boulekbache-Makhoul, Madani, et al., 2022). Microwave drying, which has been widely studied over the past decade to process not only liquid samples but also various types of solid materials, including food, vegetables, fruits, woody materials, and ores, is currently attracting the interest of researchers as an alternative of nonconventional heating source for biomass and waste processing associated with dielectric heating effects (Miccio et al., 2020).

When compared with existing drying techniques, the microwave method saves time and energy and also produces high-quality end products (Keser et al., 2020; Liu, Dai, et al., 2020).

Mathematical models have been used to study the drying behavior and kinetics of agricultural products, which allows the control of drying process. Thin-layer drying equations are important tools in mathematical drying modeling and to use these equations, the drying rate curves must be known (Erbay & Icier, 2010).

Recently, various mathematical thin-layer models that describe drying phenomena are classified into theoretical, semitheoretical, and empirical models. The last two categories consider only the external resistance to moisture transfer. These models neglect the effect of sample temperature variation on the drying process. Many of these models give a reasonably good regression to the experimental drying data, but are limited to the processing conditions due to their empirical nature (Krishna Murthy & Manohar, 2012).

Several studies reported the application of microwaves in the drying of fruits such as lemon slices (Darvishi et al., 2014), Sorbus fruit (Lüle & Koyuncu, 2015), crispy bananas (Monteiro et al., 2015), blueberries (Zielinska & Markowski, 2016), lemon slices (Kesbi et al., 2016), nectarine slices (Miraei Ashtiani, Sturm, & Nasirahmadi, 2017) pomelo (Yildiz & İzli, 2019), apple slices (Dai et al., 2019), and dragon fruit (Bhagya Raj & Dash, 2021).

Alibas and Yilmaz (2022), investigated microwave and convective drying by providing results on the thermal properties of orange slices, the effect of drying on some phytochemical parameters (color parameters L , a , b , C , α° , and ΔE , browning index, whitening index, and ascorbic acid), and modeling using 21 thin-layer drying equations. The results closest to the experimental data were obtained with the modified Henderson and Pabis equation for all microwave drying powers and all convection drying temperatures. Alibas et al. calculated the effective moisture diffusions (3.277×10^{-09} to 1.221×10^{-07} at 90 and 1000 W, and 2.702×10^{-09} to 1.362×10^{-08} at 50°C and 125°C), and activation energy using the drying data. Some thermal properties such as specific heat, thermal conductivity, thermal diffusivity, and thermal effusivity were calculated and recorded as decreasing in all thermal properties with drying. After calculating the energy

consumption of both drying methods, Alibas and Yilmaz observed that microwave drying was the most efficient. They concluded that the most suitable drying method is microwave drying at average powers of 350 and 500 W considering the drying and quality parameters.

To our knowledge, no work has been reported in the literature on the valorization of blood orange (*Citrus sinensis* [L.] Osbeck) carried out with zero waste, and its drying in thin-layer assisted by microwaves; as well as the comparison of this process with convective drying by modeling with 38 models.

However, the above authors did not address the energy consumption, which allows to identify the best drying process regarding energy efficiency. This information is needed by industrialists for efficient management of drying techniques and better energy use (Mouhoubi et al., 2020).

The objective of this research is to study and compare the drying behavior of blood orange slices under ventilated microwave (200–800 W) and ventilated parboiler (40°C–120°C) drying conditions, to select the best model among the 38 mathematical drying models cited in the literature that describe the phenomenon, to describe the moisture removal behavior and evaluate the evolution of the drying rate kinetics and its variation with the water content, and finally to calculate the effective diffusivities, the activation and consumption energies reflecting microwaves power or convective drying effects.

2 | MATERIALS AND METHODS

2.1 | Materials

The blood orange (*C. sinensis* [L.] Osbeck) fruits samples used in this drying experiment were collected from Oued-Ghir, in Bejaia region, a province located in northeastern Algeria. They were washed with tap water and then with distilled water and stored at low temperature before being subjected to the drying process (microwave and convective at different power and temperatures). Then, they were allowed to reach room temperature (24°C ± 1°C) for about an hour before starting the work. The orange is cut into thin slices; the average thickness was 7.50 ± 0.12 mm is measured with a caliper.

2.2 | Phenomenological drying

The original water content of fresh orange was 84.30% ± 1.08% wb using forced air convection convective drying.

Two different drying techniques were used. The drying treatment with a domestic digital microwave oven (LG MH6336GIH, China) was carried out with the following characteristic: 230 V, a frequency of 2450 MHz. The microwave oven has the ability to work at different output power, namely 200, 400, 600, and 800 W. The size of the microwave space is 476 (W) × 272 (H) × 388 (D) mm, and consists of a rotating glass plate with a diameter of 300 mm at the oven base. The output power level and duration of microwave treatment were determined by a digital control.

Hot air drying (40°C, 60°C, 80°C, 100°C, and 120°C) was performed using a conventional laboratory oven (Memmert Model UFB 400, with forced air circulation, GmbH + Co. KG, Germany), with following technical data 230 V, 6.1 A 50/60 Hz 1400 W.

During drying tests, each sample (100 g) of thin-layer drying experiments, consisting of blood orange slices was placed on plates, and placed in both devices. Moisture loss was measured periodically using a digital balance with an accuracy of 0.01 g (RADWAG, WPS 600/C/2).

Three repetitions of each experiment were performed and the presented data are an average of these results. The drying process was continued until the sample weight reached a constant weight corresponding to a moisture content of 9.38 ± 0.25.

2.3 | Mathematical modeling

The moisture ratio (MR) and DR of blood orange slices during MD and CD at different power levels and temperatures were estimated by the following Equation (1):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

Usually, the value of M_e is very small with M_t and M_0 , then it can be considered irrelevant for MR calculation, Therefore, Equation (2) can be simplified to Equation (3), which was used in this work for MR values determination: (Doymaz & Sahin, 2016)

$$MR = \frac{M_t}{M_0} \quad (2)$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (3)$$

where M_t , M_0 , and M_e (kg water/kg dry matter) are moisture content at any time, initial moisture content and equilibrium moisture content, respectively; the M_{t+dt} is moisture content at $t + dt$ (kg water/kg dry matter) and t is drying time (min).

Several mathematical models have been proposed to describe the drying characteristics of agricultural products. In this study, 38 models (Table 1) from literature were used to model the drying kinetics of blood orange slices.

2.4 | Determination of effective moisture diffusivity

Moisture diffusivity is assumed to be the only physical mechanism explaining the evaporation of water from the matrix surface during water transfer. Fick's second law of unsteady state diffusion was chosen to determine the moisture diffusivity of blood orange slices described in the following Equation (4):

TABLE 1 Mathematical models given by various authors for drying curves

Name	Mathematical equation
1 Ademiluyi modified	$MR = a \exp(-kt)^n$
2 Aghabashlo Model	$MR = \exp - [(-kt^n) + bt] + c$
3 Alibas	$MR = a \exp(-k_1 t)$
4 Balbay and Sahin	$MR = (1 - a) \exp(-kt^n) + b$
5 Binomial	$MR = a \exp(-k_0 t) + b \exp(k_1 x_1)$
6 Chavez-Mendez et al.	$MR = [1 - (1 - L_2) L_1 t]^{1/(1 - L_2)}$
7 Combined two term and page	$MR = a \exp(-kt^n) + b \exp(-ht^n)$
8 Demir et al.	$MR = a \exp(-kt)^n + b$
9 Diffusion approach	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$
10 Fernando and Amarasinghe	$MR = (1 + at + bt^2)/(1 + ct)$
11 Geometric	$MR = at^{(-n)}$
12 Hasibuan and Daud	$MR = 1 - at^n \exp(-kt^n)$
13 Henderson and Pabis	$MR = a \exp(-kt)$
14 Hii et al.	$MR = a \exp(-kt^n) + c \exp(-k_1 t^n)$
15 Hustrulid and Flikke	$MR = a \exp(-kt)$
16 Lewis	$MR = \exp(-kt)$
17 Logarithmic	$MR = a \exp(-kt) + c$
18 Logistic	$MR = b/[1 + a \exp(kt)]$
19 Midilli and Kucuk	$MR = a \exp(-kt^n) + bt$
20 Modified Henderson and Pabis	$MR = a \exp(-kt) + b \exp(-k_1 t) + c \exp(-K_2 t)$
21 Modified Midilli	$MR = \exp(-kt) + bt$
22 Modified Page I	$MR = \exp(-kt)^n$
23 Modified Page II	$MR = \exp[-c(t/L^2)^n]$
24 Modified Page III	$MR = k \exp(-t/d^2)^n$
25 Newton	$MR = \exp(-kt)$
26 Page	$MR = \exp(-kt^n)$
27 Parabolic	$MR = c + bt + at^2$
28 Silva et al.	$MR = \exp(-at - bt^{1/2})^{1/2}$
29 Simplified Fick's diffusion equation	$MR = a \exp(-k[t/L^2])$
30 Singh et al.	$MR = \exp(-kt) - akt$
31 Sledz et al.	$MR = b \exp(-kt)/(1 + a \exp(k_1 t))$
32 Taghian Dinani et al.	$MR = a \exp[-([t - b]/a)^2]$
33 Two terms	$MR = a \exp(-kt) + b \exp(-k_1 t)$
34 Two terms exponential	$MR = a \exp(-kt) + (1 - a) \exp(-kat)$
35 Vega Lemus	$MR = (a + kt)^2$
36 Verma et al.	$MR = a \exp(-kt) + (1 - a) \exp(-k_1 t)$
37 Wang and Singh	$MR = 1 + at + bt^2$
38 Weibull	$MR = \exp(-[t/a]^b)$

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

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

Where, D_{eff} is the effective moisture diffusivity (m^2/s) and M is the material moisture content (kg water kg^{-1} dry matter).

The second thin-layer Fick's law was solved by assuming that mass transfer occurs only by diffusion and that the diffusion coefficient is constant, which is described with the following Equation (5) (Özbek & Dadali, 2007)

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

When the mass transfer Fourier number is >0.2 , Equation (5) can be simplified to Equation (6):

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

Thus:

$$F_0 = -0.101 \ln(MR) - 0.0213 \quad (7)$$

Thus, to calculate the effective moisture diffusivity, the Equation (8) below was used to determine it at different drying microwave-powers and convective-temperatures.

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

Where D_{eff} is the effective diffusivity (m^2/s), t is the drying process time (s), $L/2$ is the half slab thickness (m) because drying occurs on both sides and MR .

2.5 | Energy consumption

Energy consumption can be evaluated using two different efficiency indices, namely specific electrical energy consumption Equation (9) or energy efficiency Equation (10) (Tsotsas & Mujumdar, 2014)

$$SEC_e = \frac{3600E}{M_s(X_i - X_f)} \quad (9)$$

where SEC_e is the specific electrical energy consumption (MJ/kg water), E is the total electrical energy consumption (kWh), X_i and X_f refer to the initial and the final moisture contents (dm), respectively, and M_s is the mass of dry solid matter (in kg).

$$EE = M_s(X_i - X_f) \frac{\Delta h_v}{3600E} \cdot 100 \quad (10)$$

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

2.6 | Activation energy

Activation energy (E_a) is the energy required for eliminating 1 mol moisture from the substance with constant compositions and given MC (Miraei Ashtiani, Salarikia, & Golzarian, 2017). This later is often described using a simple Arrhenius exponential relationship to study the effect of temperature. For this purpose, in the case of hot air drying: Equation (11) linking temperature to the effective moisture diffusivity was used (Chen et al., 2020).

$$D_{\text{eff}} = D_0 \exp\left(\frac{-E_a}{RT}\right) \quad (11)$$

$$D_{\text{eff}} = D_0 \exp\left(\frac{-E_a m}{P}\right) \quad (12)$$

where D_{eff} is the effective diffusivity (m^2/s), D_0 are the pre-exponential factor of the Arrhenius equation (m^2/s) for convective and microwave drying, respectively, R is the universal gas constant (8.314 kJ/mol K), T is absolute air temperature (K), m is the mass of raw sample (g), P is the power (W) and E_a is the activation energy expressed in (kJ/mol) for hot air drying and in (W/g) for microwave drying.

2.7 | Goodness-of fit statistics

The goodness of fit and the model's discrimination has been evaluated by coefficients of determination (R^2), χ^2 (χ^2) Equation (13) and root mean square error (RMSE) Equation (14). Higher of (R^2), smaller of χ^2 , smaller of RMSE, and a random distributed of residual indicate the adequacy of the experimental data to the model. The statistical values are determined as follows (Guemouni et al., 2022):

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

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

where MR_{exp} is experimental moisture ratio (dimensionless), MR_{pre} is predicted moisture ratio (dimensionless) and equilibrium moisture

content, respectively, and N is the number of data points and Z is the number of the constant parameters in the thin-layer drying models (Agbede et al., 2020; Krishna Murthy & Manohar, 2012). Analysis of variance (ANOVA) was performed using JMP 13 software. Tukey's multiple range test (HSD) was used to compare means of estimated kinetic parameters. Evaluations were based on the $p < .05$ significance level.

3 | RESULTS AND DISCUSSION

3.1 | Microwave versus convective drying

3.1.1 | Drying curves

Figure 1a,b illustrates the drying curves of blood orange slices by microwave and convection, these results show the variation of moisture content with drying time.

Regardless of the drying process, it was observed that the moisture ration decreased rapidly at both high and low power levels. As the drying process progressed, the drying rate was faster at the beginning and gradually decreased beyond a given period. Over time, the loss of moisture in the fruit resulted in a decrease in the absorption of microwave power and thus a reduction in the drying rate (Dash et al., 2020). Increasing the microwave power accelerated the drying process to reach an average equilibrium moisture content of 4%wb after 54 min at 200 W and 15.5 min at 800 W. While for the convective drying, this average equilibrium water content was reached after 5520 min at 40°C and 70 min at 120°C.

The advantage of using microwave for a significant reduction of drying time has been found in other works for different fruits (Agbede et al., 2020; Amini et al., 2021; Bennaceur et al., 2021; Chen et al., 2020; Mouhoubi et al., 2020).

3.1.2 | Variation of drying rate with drying time

Drying rate as a function of drying time is shown in Figure 2a,b. In microwave drying, it was noticed that up to a certain level, drying rate increases with drying time and progressively decreases. As expected, to remove the residual water after maximum drying rate, more time is required, which reduces the drying rate. Consequently, the average drying rate varies between 0.08 kg water/kg dm min, at 200 W and 0.29 kg water/kg dm min, at 800 W. While in the convection drying a different pace was observed, see the absence of the increase phase. Therefore, the average drying rate varies between 0.001 kg water/kg dm min, at a temperature of 40°C and 0.04 kg water/kg dm min, at a temperature of 120°C. This result can be explained by the effect of microwave exposure, the absorbed radiation increases rapidly the temperature of water in situ, which rise water diffusivity, evaporation, leading to cell tissue destruction. Similar paces for both convective and microwave drying, have been reported in previous studies (Agbede et al., 2020).

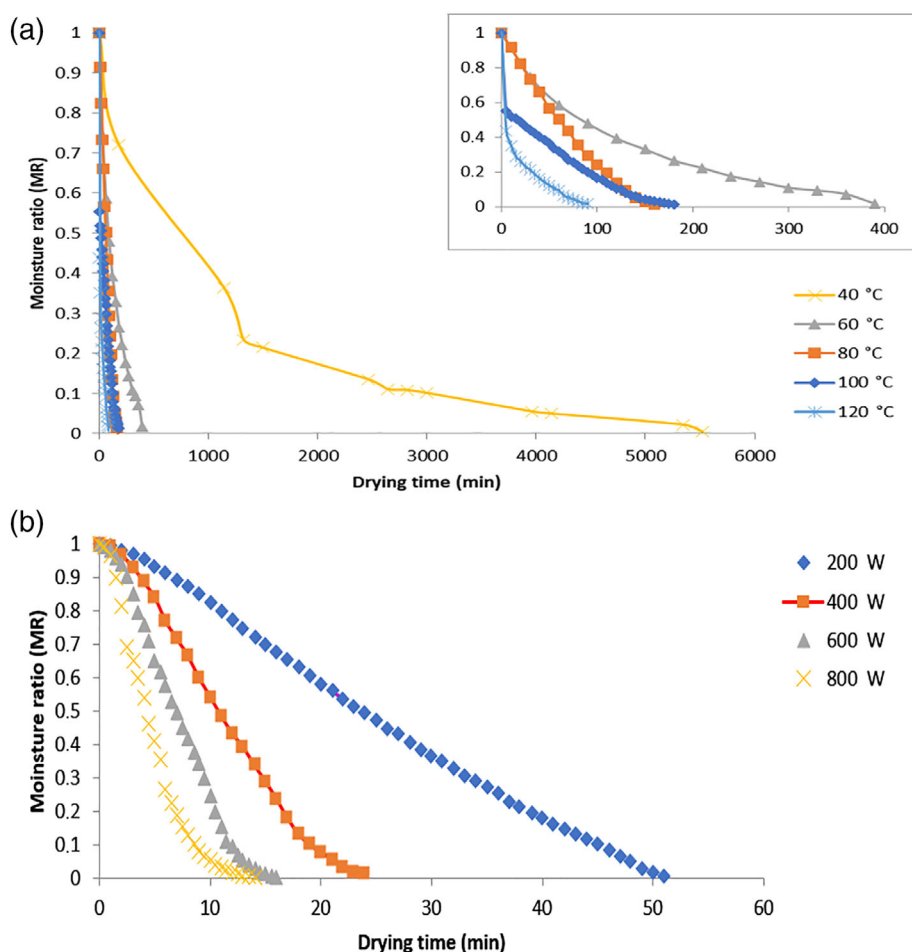


FIGURE 1 Change in experimental moisture ratio with drying time at various temperatures (a) and microwave drying at various power levels (b)

3.1.3 | Variation of drying rate versus moisture content

The variation of drying rate with moisture content, which explains the microwave and convective drying behavior of blood orange slices, is shown in Figure 3a,b. Nevertheless, after a brief period when high drying rates prevailed, the drying rates started to decrease rapidly from a given critical moisture content, then continued to decrease slowly with decreasing moisture content and took longer to remove the remaining moisture, this pattern has already been described in previous researchers works (Bishnoi et al., 2020; Darvishi et al., 2014; Hidar et al., 2020; Horuz et al., 2017), which is explained by the fact that at the beginning of drying, the free moisture content is removed. At this stage, a decrease in drying rate with a decrease in moisture content is rapid. Below the specific moisture content, the remaining moisture is bound to the matrix, which has lengthened the internal moisture transfer pathways and generates the decrease in drying rate, drying has become limited by moisture transfer (Bennaceur et al., 2021; Chen et al., 2020). In fact, increasing the microwave power and temperatures significantly increased the average drying rate to 23.59 and 28.86 kg water/kg dm min kg dry matter min⁻¹ at 600 and 800 W (about 3.5 times that at 200 W) and 1.26 and 2.00 kg water/kg dm min kg dry matter min⁻¹ at 100°C and 120°C (about 14, 3 times that at 40°C), respectively.

These results were in agreement with the studies of Bennaceur et al. (2021) and Evin (2012), and Mouhoubi, Boulekbache-Makhlouf, Mehaba, et al. (2022).

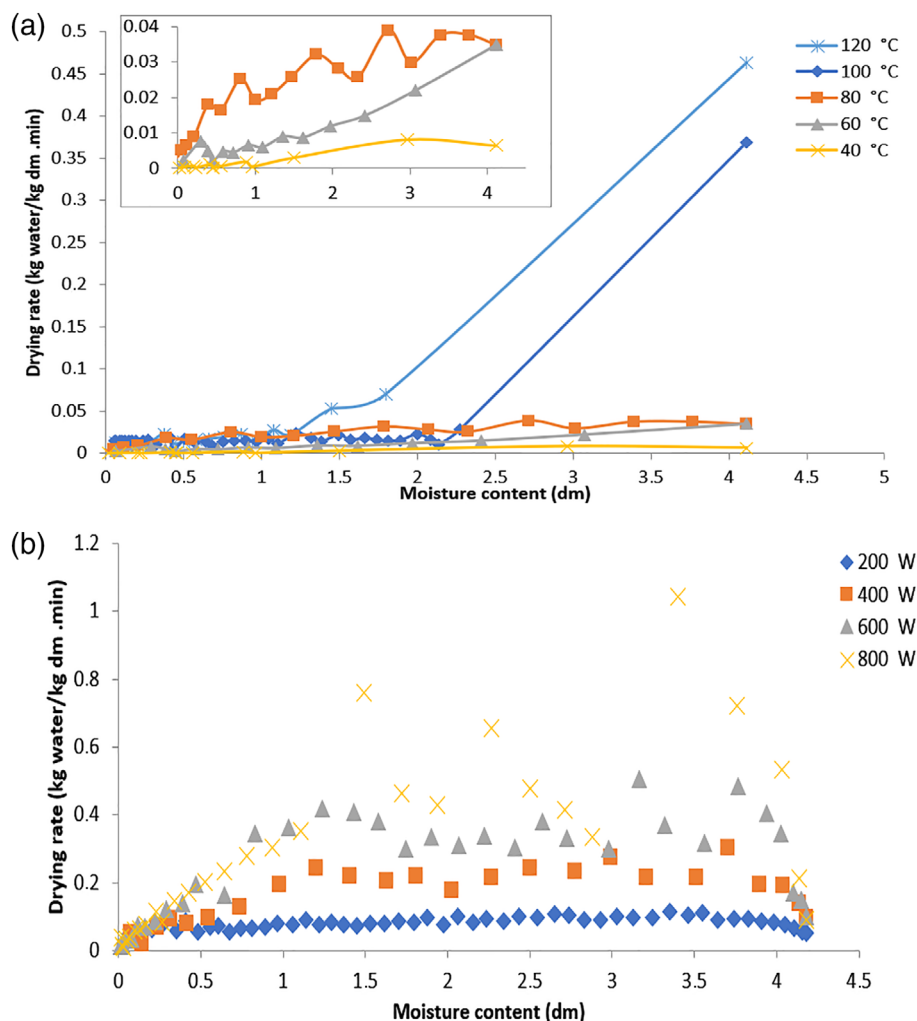
Thus, it should be noted that during drying, the rate of drying is proportional and the drying time is inversely proportional to the level of microwave power and temperatures.

The statistical analysis shown in Table 2, showed that the highest drying rates between two processes were induced by the application of microwave drying, especially when high powers were applied. This can be explained by the fact that microwaves have the advantage of reducing drying time which is related to rapid absorption of energy by water molecules, causing their rapid evaporation (Doymaz & Sahin, 2016).

3.2 | Thin-layer empirical mathematical models

In order to model the drying data in the present study, 342 fittings for 38 thin-layer models were used, while, the results of three best model ($R^2 > 0.97$) among them were shown in Tables 3 and 4 which correspond to convective and microwave drying treatment, respectively. The goodness of tested models fit to the experimental data is based on determination coefficient (R^2), χ^2 , and RMSE. The higher R^2 values and

FIGURE 2 Change in drying rate with moisture content at various temperatures (a) and microwave drying at various power levels (b)



the lower χ^2 and RMSE values, better was the fit of the model to the experimental data. Midilli and Kucuk model was selected as the best fit for fit convective drying while Sledz model was selected for microwave once (Tables 3 and 4). It should be noted that the Midilli model successfully described convective drying behavior of many agricultural products. (Mbegbu et al., 2021; Zannou et al., 2021). Sledz model has also been chosen in previous studies to describe microwave drying behavior (Mouhoubi et al., 2020; Sledz et al., 2016, 2017).

3.3 | Effective moisture diffusivity

The diffusion coefficient indicated the mass transport rate during drying process; it can be used to describe how moisture is removed per unit of time under specific conditions. During microwave and convective drying process, the effective diffusivities in blood orange samples from the internal structure to the external environment was illustrated in Table 2.

These values range from 0.07×10^{-9} to 1.97×10^{-9} m²/s and from 2.07×10^{-9} to 15.67×10^{-9} m²/s for forced convection and microwave drying, respectively.

The D_{eff} values recorded in this study are within the general range of 10^{-12} – 10^{-8} m²/s for drying agricultural materials (Azeez et al., 2019; Miraei Ashtiani et al., 2022). The reasons for these differences in D_{eff} values of different products are related to differences in varieties, cellular structure, initial and final MC, dimensions and sample shape, applied technique, and drying equipment (Miraei Ashtiani, Sturm, & Nasirahmadi, 2017).

The D_{eff} values obtained in this study were comparable to the values of other study reported for lemon slices microwave drying, the values were 1.87×10^{-10} to 3.59×10^{-10} m²/s (Darvishi et al., 2014).

An increase in effective moisture diffusivity with increasing temperature has also been discussed (Agbede et al., 2020; Chen et al., 2020; Doymaz & Sahin, 2016) which is explained by the fact that increasing temperature strongly activates water molecules, which in turn accelerate their transfer to the matrix surface (Amami et al., 2017; Aral & Beşe, 2016). However, its increase when using microwave drying process and it is related to the energy absorbed by moisture, which increases with the increment of microwave power level (Agbede et al., 2020; Zhu et al., 2015).

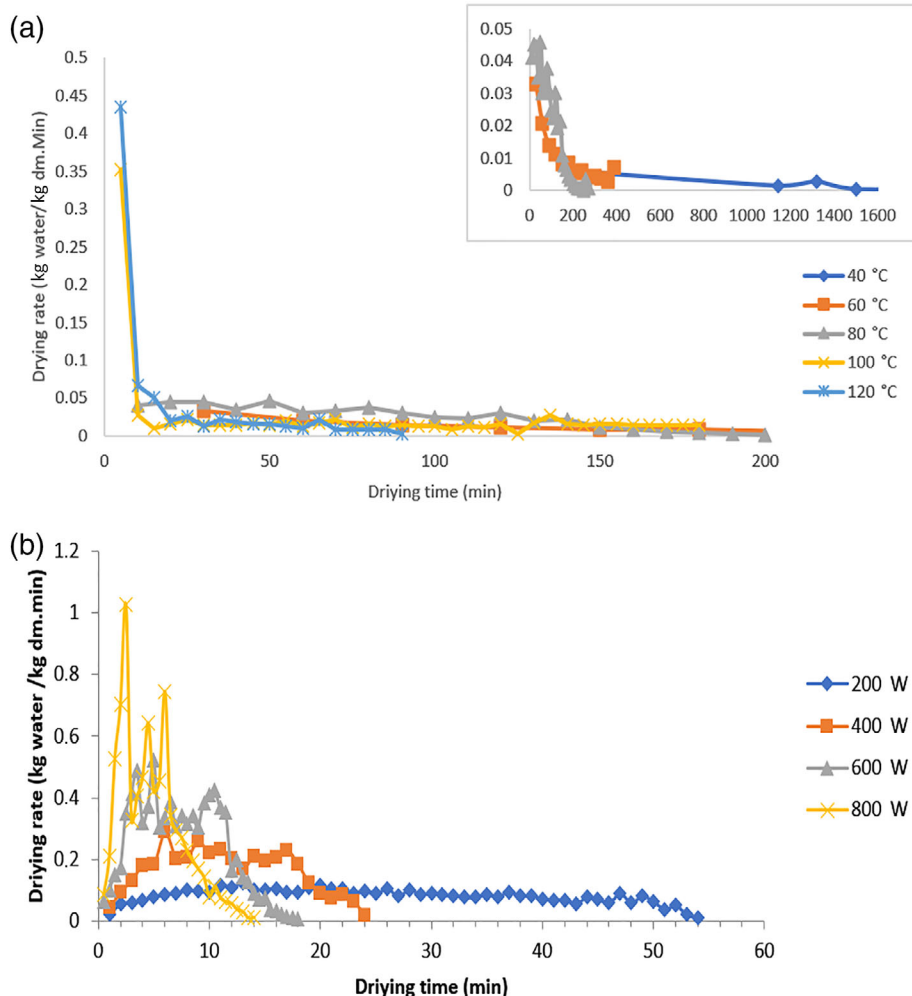


FIGURE 3 Change in drying rate with drying time at various temperatures (a) and microwave drying at various power levels (b)

TABLE 2 Statistical analysis of drying parameters

Parameters						
		Dt (min)	DR ($\times 10^{-2}$) (kg H ₂ O/kg dm.min)	D _{eff} ($\times 10^{-9}$) (m ² /s)	SEC _e ($\times 10^7$) (MJ/kgH ₂ O)	EE ($\times 10^{-2}$) (%)
T (°C)	40	5521.0 \pm 7.94 ^{aA}	0.14 \pm 0.02 ^{dF}	0.07 \pm 0.0 ^{aC}	29.35 \pm 1.16 ^{aA}	0.08 \pm 0.00 ^{dG}
	60	359.83 \pm 6.53 ^{bB}	0.79 \pm 0.03 ^{cEF}	0.60 \pm 0.13 ^{aC}	2.04 \pm 0.16 ^{bB}	1.17 \pm 0.09 ^{cFG}
	80	270.50 \pm 5.07 ^{cC}	1.40 \pm 0.01 ^{bEF}	0.94 \pm 0.10 ^{aC}	1.72 \pm 0.15 ^{bcBC}	1.39 \pm 0.12 ^{cFG}
	100	180.17 \pm 5.11 ^{dD}	1.26 \pm 0.09 ^{bEF}	1.68 \pm 0.09 ^{aBC}	0.93 \pm 0.05 ^{bcCD}	2.55 \pm 0.15 ^{bF}
	120	90.33 \pm 4.04 ^{eE}	2.00 \pm 0.25 ^{aE}	1.97 \pm 2.70 ^{aBC}	0.49 \pm 0.05 ^{cD}	4.93 \pm 0.54 ^{aE}
P (W)	200	54.33 \pm 5.30 ^{aF}	8.28 \pm 0.54 ^{dD}	2.07 \pm 0.61 ^{bBC}	0.25 \pm 0.01 ^{aD}	9.02 \pm 0.37 ^{dD}
	400	24.17 \pm 2.47 ^{bG}	16.16 \pm 0.32 ^{cC}	6.00 \pm 2.49 ^{bBC}	0.10 \pm 0.00 ^{bD}	22.18 \pm 0.36 ^{cC}
	600	17.83 \pm 1.61 ^{bcG}	23.59 \pm 1.16 ^{bB}	8.02 \pm 1.14 ^{aB}	0.08 \pm 0.00 ^{cD}	27.92 \pm 0.77 ^{bB}
	800	13.83 \pm 1.04 ^{cG}	28.86 \pm 1.21 ^{aA}	15.67 \pm 5.42 ^{aA}	0.06 \pm 0.00 ^{dD}	36.93 \pm 0.96 ^{aA}

Note: Table shows mean values with SD of the mean. ^{a-e}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-G}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.

Abbreviations: D_{eff}, effective diffusivity; DR, drying rate; EE, electrical energy; SEC_e, specific electrical energy consumption.

Statistical analysis of the D_{eff} values obtained for the same drying process showed that there were no significant differences between values obtained for all temperatures when using convective drying process. The

application of low power levels (200–400 W) in microwave drying did not lead to a significant difference in D_{eff} values; however, a significant difference in D_{eff} values is recorded at power levels of 600 W or see more.

TABLE 3 The values of the drying constants and coefficients and the statistical parameters of the best models for all the drying temperature

Models	T (°C)	The drying constants and coefficients				Statistical parameters		
Midilli and Kucuk		<i>a</i>	<i>k</i>	<i>n</i>	<i>b</i>	R^2	χ^2	RMSE
	40	0.9975	0.0115	0.6546	0.0000	0.9955	0.0006	0.0192
	60	10.017	0.0195	0.7850	−0.0002	0.9980	0.0002	0.0125
	80	0.9849	0.3111	12.570	−0.0004	0.9987	0.0002	0.0115
	100	0.9989	0.3804	0.1737	−0.0025	0.9930	0.0004	0.0179
	120	10.000	0.4764	0.3284	−0.0019	0.9995	0.0000	0.0054
Fernando and Amarasingh		<i>a</i>	<i>b</i>	<i>c</i>		R^2	χ^2	RMSE
	40	0.0001	0.0000	0.0022		0.9933	0.0008	0.0242
	60	−0.0005	0.0000	0.0098		0.9982	0.0002	0.0118
	80	−0.0102	0.0000	−0.0008		0.9997	0.0000	0.0052
	100	0.3579	−0.0023	0.7272		0.9895	0.0005	0.0219
	120	0.1117	−0.0018	0.4817		0.9991	0.0001	0.0073
Modified page II		<i>c</i>	<i>L</i>	<i>n</i>		R^2	χ^2	RMSE
	40	0.0115	12.304	0.7014		0.9943	0.0006	0.0210
	60	0.0159	11.967	0.9179		0.9950	0.0005	0.0196
	80	0.0087	15.407	13.624		0.9951	0.0006	0.0221
	100	0.0727	0.6763	0.6004		0.9247	0.0037	0.0586
	120	0.0771	−0.2405	0.5102		0.9907	0.0003	0.0166

TABLE 4 The values of the drying constants and coefficients, and statistical parameters of the best models for all microwave power level

Models	P (W)	The drying constants and coefficients				Statistical parameters		
Sledz et al.		<i>b</i>	<i>k</i>	<i>a</i>	<i>k</i> ₁	R^2	χ^2	RMSE
	200	10.500	0.0220	0.0118	0.1239	0.9977	0.0002	0.0151
	400	10.612	0.0263	0.0369	0.2740	0.9987	0.0002	0.0126
	600	0.9970	0.0678	0.0085	0.5081	0.9970	0.0004	0.0192
	800	71.978	0.4943	60.037	−0.4769	0.9977	0.0003	0.0164
Logistic		<i>b</i>	<i>a</i>	<i>k</i>		R^2	χ^2	RMSE
	200	11.490	0.1537	0.0908		0.9953	0.0005	0.0213
	400	10.961	0.0936	0.2510		0.9982	0.0003	0.0150
	600	10.851	0.0836	0.3860		0.9948	0.0007	0.0254
	800	12.264	0.1974	0.4775		0.9977	0.0003	0.0165
Parabolic		<i>a</i>	<i>b</i>	<i>c</i>		R^2	χ^2	RMSE
	200	10.479	−0.0250	0.0001		0.9986	0.0001	0.0118
	400	10.980	−0.0704	0.0010		0.9885	0.0016	0.0375
	600	11.027	−0.1035	0.0020		0.9882	0.0017	0.0383
	800	10.932	−0.1741	0.0069		0.9933	0.0009	0.0281

Statistical analysis of the D_{eff} values for both drying processes showed that the values recorded for all temperatures are not statistically different from those registered at 200 and 400 W.

Therefore, 600 and 800 W powers are much higher, and show significant differences between them, between them and the rest of all other D_{eff} values. These results are very similar to those of Mouhoubi et al. (2020).

3.4 | Activation energy

Activation energy is the energy used to break the bond between the moisture particles and it is inversely proportional to the effective moisture diffusivity. The calculation of the activation energy for both drying processes: convection and microwave were determined by estimating the coefficients using Equations (11) and (12). The

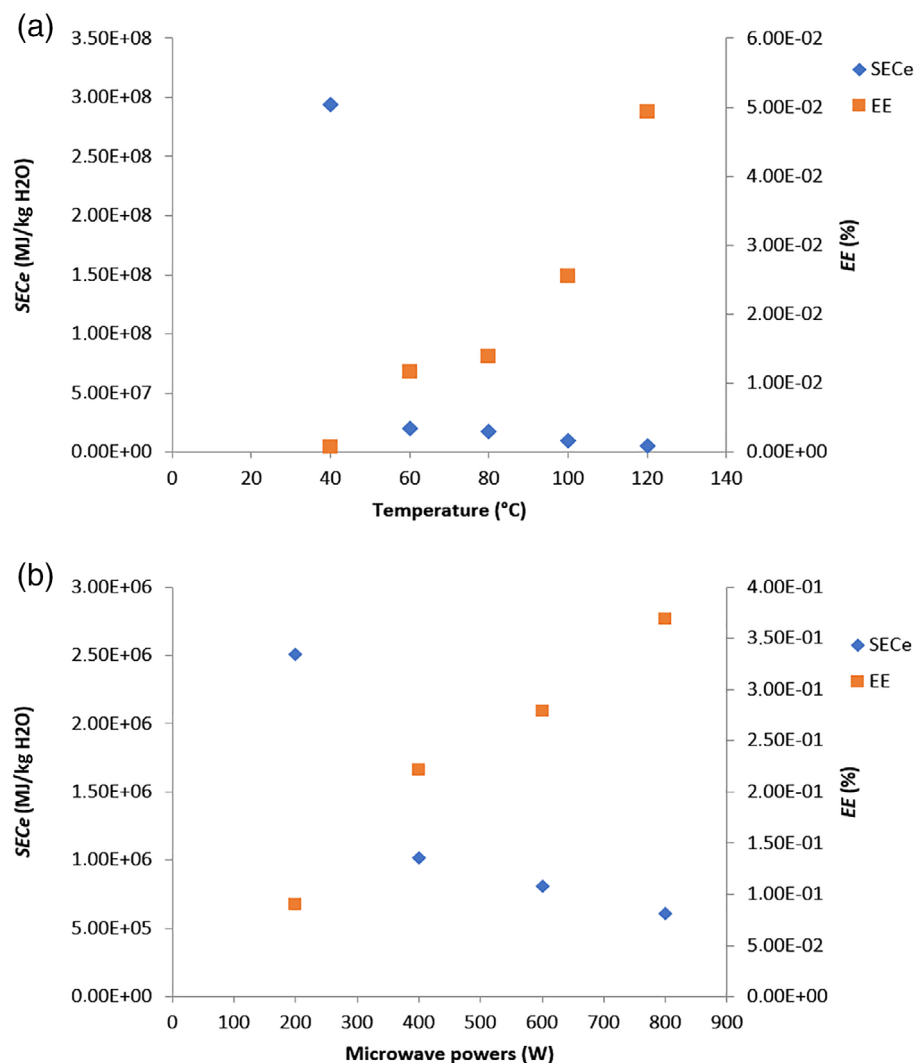


FIGURE 4 Variations in specific electrical energy consumption (SECe) and electrical energy (EE) values (a) convective drying and (b) microwave drying

obtained values for drying processes were estimated to be 23.53 kJ/mol for convection and 8.87 W/g for microwave.

On one hand, the reported E_a values during convection drying are in the general range of 12.7–110 kJ/mol for fruits and vegetables (Aral & Beşe, 2016) and they were very close to the value obtained by Alibas and Yilmaz (2022), during orange slices drying with E_a of almost 20.5 kJ/mol.

And slightly lower values reported in literature, when drying nectarine slices (31.28 and 35.23 kJ/mol at temperatures ranging from 50°C to 70°C; Alaei & Chayjan, 2015), orange peel (34.19 kJ/mol; Deng et al., 2019), tomato slices (31.19 kJ/mol; Azeez et al., 2019), mango ginger (32.6 kJ/mol; Krishna Murthy & Manohar, 2014), walnut kernel (31.63 kJ/mol; Chen et al., 2020), and pumpkin (33.74 kJ/mol; Guiné et al., 2011).

On the other hand, the E_a values obtained during microwave drying were close to that recorded for lemon slices (10.911 W/g; Darvishi et al., 2014), for okra (5.54 W/g; Dadalı, Kılıç Apar, & Özbek, 2007), for basil leaves (11.41 W/g; Demirhan & Özbek, 2009), but lower than those reported previously for drying kiwi slices (21.38 W/g; Darvishi et al., 2016), *Hypericum perforatum*

L. (28.68 W/g; Ilknur Alibas & Kacar, 2016), orange slices (60 W/g; Alibas & Yilmaz, 2022), and Ximeng lignite (77.0485 W/g; Zhu et al., 2015).

The variability in E_a values can be linked to the difference in variety, specific surface thickness, and maturation state of the products, pretreatments, and applied drying conditions (Deng et al., 2019; Jha et al., 2021).

3.5 | Energy consumption

The energy consumed during each of the two drying processes and the different levels applied for each of them was evaluated by calculating two indices: SEC_e and EE. The results of calculations of these indices were presented in Table 2.

As shown in Table, the SEC_e decreases when moving from low temperatures or power levels to higher temperatures or power levels for convection and microwave drying, respectively. The values thus vary over the ranges of 0.49×10^7 to 29.35×10^7 and 0.06×10^7 to 0.25×10^7 MJ/kg H₂O in the same respective order.

An opposite behavior was observed for the EE variations, EE values increase when moving from low temperatures or power levels to high temperatures or power levels. The EE values range from $0.08 \times 10^{-2}\%$ to $4.93 \times 10^{-2}\%$ and for $9.02 \times 10^{-2}\%$ and $36.93 \times 10^{-2}\%$ convective and microwave drying, respectively. The simultaneous variation of these two parameters was illustrated in Figure 4a,b.

Statistical analysis showed clear significant differences for the SEC_e values of microwave drying for all powers used and for the values obtained after drying at the temperature of 40°C and 120°C. The same is true for the EE values except for the temperatures of 60°C and 80°C which did not show significant differences.

Statistical analysis of the SEC_e values for both drying processes showed that the highest energy consumption was attributed to the temperature of 40°C, which showed a significant difference with respect to all temperatures and power levels, while no significant difference was observed for all powers used, as well as for the high temperatures (100°C and 120°C). Regarding energy efficiency, a significant difference was observed after switching from one power level to another, which in turn differed at all temperatures. Furthermore, overlaps are observed for the EE values obtained for all temperatures except for 120°C.

Comparatively, it appears that the highest energy consumption was obtained for convection drying (49×10^7 MJ/kg H₂O) and the highest energy efficiency was obtained for microwave drying (0.25×10^7 MJ/kg H₂O). This suggests that energy consumption is proportionally related to drying time, while efficiency is inversely related to drying time. It is worth noting similar trends have been reported by Alibas (2014), Amiri Chayjan and Shadidi (2014), Darvishi et al. (2014), Kaveh et al. (2021), Maftoonazad et al. (2020), Sledz et al. (2017), Zarein et al. (2013).

4 | CONCLUSION

This study focuses on modeling the kinetics of thin-layer drying *C. sinensis* [L.] Osbeck slices, as well as the energetic aspects of microwave and convective drying. The microwave drying used, significantly reduced the drying time and was effectively used to dehydrate our fruit, to convective drying.

In total, 38 mathematical models of thin-layer drying were applied to explain the drying kinetics. The models of Midilli and Kucuk and Sledz models were the best fit for convective and microwave drying, respectively.

The drying rate and moisture diffusivity increased with increasing order of temperature and applied power. The reduction in moisture content during drying resulted in an amplification of the effective moisture diffusivity. The highest energy consumption was attributed to convective drying while the highest energy efficiency was attributed to microwave drying.

The present obtained results study demonstrates that the microwave drying technique can be used to the best dehydrate blood orange.

This work is important not only because it provides a significant reference for time, heat, and energy efficient drying technique for industrial production of orange slices and powder, but also because it allows the recovery of the whole fruit with zero waste.

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CONFLICT OF INTEREST

We wish to confirm that there are no know conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in [repository name] at [DOI].

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