

Convective and microwave drying of coriander leaves: Kinetics characteristics and modeling, phenolic contents, antioxidant activity, and principal component analysis

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Abstract

In this study, coriander leaves were subjected to two different drying techniques: convective (40, 80, and 120°C) and microwave (100, 500, and 1,000 W). The effects of both processes on the kinetic parameters variation, modeling, and phytochemical quality were studied. Kinetic parameters variation showed that time reduction (2.53 min), high drying rate (3.08 kg water/kg dm min), and high diffusivity ($1.21 \times 10^{-10} \text{ m}^2/\text{s}$) were obtained during microwave drying. For energy consumption, an opposite trend was observed between the variation in the specific electrical energy consumption (SEC_e), which is significant during convective drying ($208.33 \times 10^{+07} \text{ MJ/kg H}_2\text{O}$), and the energy efficiency (EE), which is obtained during microwave one ($12.16 \times 10^{-03}\%$). The kinetic data modeling done on 23 empirical models allowed us to choose the Sledz model as the best describing the drying kinetics of coriander since it presented better predictive performances with $.9947 < \text{adjusted } R^2 < .9995$, $0.0001 < \chi^2 < 0.0005$, and $0.0070 < \text{RMSE} < 0.0228$ values. In relation to the bioactive compounds, the highest values of the total phenolic content (TPC) and antioxidant activities (ABTs and DPPH) were observed during microwave drying with 0.37 mg GAE/mL, 83.33, and 71.94%, respectively. Correlations between kinetic parameters, energy consumption as well as phytochemical quality were established using principal component analysis (PCA). As a result, the innovative microwave process proved to be the best method for drying coriander leaves.

Practical applications: The evolution of technological conservation processes has led to the development of a wide range of modern drying processes. The success of these processes can be explained by the many advantages attributed to them: shorter drying times, high drying rate, high energy efficiency, and product quality. The most difficult is the appropriate choice of a drying method with highly energy efficient and consumes less energy while maintaining the best quality. Fresh coriander leaves are widely used to flavor foods. However, they are highly perishable and require

immediate processing or preservation. Thus, the objective of this study is to compare two drying processes, convective and microwave drying of coriander leaves based on kinetic data, modeling, calculation of moisture diffusivity and energy consumption, as well as evaluation of the dried powders quality. The results obtained will be useful for the technological design of convective or microwave drying for coriander leaves preservation.

1 | INTRODUCTION

Coriander (*Coriandrum sativum* L.) is an annual herb from the Apiaceae family (Umbelliferae). Its fresh green leaves, with a unique aroma, are widely used in cooking, as food flavoring or to disguise the unpleasant odors of some foods. However, they are very perishable and need immediate treatment or preservation. To this end, one of the preservation processes used for coriander leaves is drying (Gao et al., 2017). It is an important method because if essential herbs are not dried immediately, or their essence is not extracted on time, they will lose their effective ingredients and their volatile compounds (Kaveh, Karami, & Jahanbakhshi, 2020).

By drying, the moisture is removed, ensuring the safety against microbial attacks and a better quality control during storage, thereby making crops available all year long (Ali et al., 2020). This process is vital for preserving food because of its effect on the quality of the dried product (Alibas, Zia, & Yilmaz, 2019). It has been used to obtain products that can be kept for long and can be applied conveniently in making formulated food products (Hnin, Zhang, Ju, & Wang, 2021).

Among the drying techniques, convective drying is the most widely used dehydration method owing to its simplicity and ease of control. However, a long convective process is very energy-consuming, which leads to the collapse of the cell structure during drying, and resulting in low quality of dried product (Sledz, Wiktor, Nowacka, & Witrowa-Rajchert, 2017).

Nevertheless, there is a rising demand for superior quality of dehydrated vegetables and leaves globally, which stimulated the need to explore for other potential drying technologies (Tarafdar, Jothi, & Kaur, 2021). That is why microwave drying has been applied as a popular alternative for drying in the food industry. The advantages of microwave drying as compared with other methods consist of operation speed (faster start-up and shut down times), low energy consumption, and precise control of process (Taghinezhad, Kaveh, Jahanbakhshi, & Golpour, 2020). Moreover, microwave dryer also has many other advantages, including high drying rate, high energy efficiency (EE), superior product quality, and efficient space use (Abbaspour-Gilandeh, Kaveh, & Jahanbakhshi, 2019). Indeed, several studies have reported the microwave application in fruits and vegetables drying such as green bean slices (Doymaz, Kipcak, & Piskin, 2016), kiwi slices (Darvishi, Zarein, & Farhudi, 2016), green apple peel (Alibas, Zia, Yilmaz, & Asik, 2019), carrot (Keskin, Soysal, Sekerli, Arslan, & Celiktas, 2019), and *Mytilus Chilensis* and *Dosidicus gigas* (Kouhila et al., 2020) as well as the drying of plants: *Hypericum*

perforatum L. (Alibas & Kacar, 2016) and green soybean (Cao et al., 2016).

An important approach for explaining the drying process is mathematical modeling (Jahanbakhshi, Kaveh, Taghinezhad, & Rasooli Sharabiani, 2020). Various mathematical models depicting the drying mechanism have been proposed in order to optimize the process and design efficient dryers. For that reason, it is important to understand the basic idea of the drying kinetics modeling of fruits and vegetables (Onwude, Hashim, Janius, Nawi, & Abdan, 2016). Moreover, energy consumption and dryer efficiency are among the important criteria of the drying process. In this context, studies for reducing the processing time and energy consumption sound necessary (Kaveh, Abbaspour-Gilandeh, & Nowacka, 2021).

Previous studies on the drying processes modeling of coriander leaves have been reported, namely on the microwave (Sarimeseli, 2011), solar (Amanlou, Tavakoli Hashjin, Ghobadian, & Najafi, 2015), and convective one (Olabinjo, Asamu, & Filani, 2020).

Sarimeseli (2011) investigated microwave drying by providing results on D_{eff} , color, rehydration capacity, and modeling using six models. The results indicated that, within the range of microwave power values, 180–360 W, effective moisture diffusivities were found to be 6.3×10^{-11} to $2.19 \times 10^{-10} \text{ m}^2/\text{s}$, and the result could successfully be presented with the model suggested by Midilli et al. Sarimeseli (2011) has also reported no significant differences in the color parameters between the fresh and dried samples, and the highest rehydration capacity was recorded for the samples dried at 180 W and lowest at 900 W.

On the other hand, Amanlou et al. (2015) have studied solar drying, so the modeling of the kinetics obtained under various conditions of temperature and speed of the air using 13 models indicate that the exponential two-term was found to have the best fit.

Olabinjo et al. (2020) studied convective drying and provided results on D_{eff} and activation energy and modeled the kinetics using 13 models. Their results revealed that Hii et al. model proved to be the most reliable and suitable model for describing the oven drying characteristics of coriander leaves under the drying temperature range and their effective moisture diffusivity ranged from $6.6577 \times 10^{-12} \text{ m}^2/\text{s}$ to $16.18652 \times 10^{-12} \text{ m}^2/\text{s}$ for the drying temperatures.

However, a detailed literature review for this study showed that there is no information on the energy consumption and EE of coriander leaves drying processes using convective hot air and microwave dryers. Hence, as an innovative study, this paper reports, for the first

time, on the energy analysis of the thin-layer drying of coriander leaves.

In view of the above limitations, the main objectives of this study are, therefore, modeling the drying kinetics of coriander leaves using 23 models, comparing the two processes; convective oven drying and innovative microwave drying based on different parameters: time, drying rate (DR), D_{eff} , SEC_e , EE, TPC, ABTs, and DPPH, and finally, establish the existing correlations between kinetic parameters, energy consumption, and phytochemical quality through PCA.

It is believed that such a study will provide information that will allow the industry to efficiently manage the drying techniques of coriander leaves by avoiding poor energy utilization while having preserved their phytochemical quality.

2 | MATERIALS AND METHODS

2.1 | Plant material

Coriander leaves were cultivated and harvested in November from the city of Biskra, Algeria, and then purchased at a local market in Bejaia, Algeria. They were separated from the stems and stored in a refrigerator at 4°C for further use. Before the drying experiments, the initial moisture content was evaluated according to the protocol of Boulekbache-Makhlouf, Slimani, and Madani (2013).

Their thickness was also measured using a caliper, and the average was found to be 0.31 ± 0.01 mm.

2.2 | Drying equipment and procedure

To reduce the moisture content of coriander leaves, two drying methods have been applied, namely conventional thermal drying in a ventilated oven and innovative microwave drying (Figure 1).

Conventional drying was conducted with a conventional oven dryer (Memmert Model UFB 400, with forced air circulation, GmbH + Co. KG, Germany), with technical features of 230 V, 6.1 A 50/60 Hz 1,400 W. This dryer has the ability to adjust the temperature in the range of 20–220°C. Microwave drying treatment was performed in a domestic digital microwave oven (Maxipower, Model MASMO23S, China), with technical features of 230 V/50 Hz and 1,400 W and an operation frequency of 2,450 MHz. The oven capacity dimensions of the microwave oven are 220 (H) × 340 (W) × 320 (D) mm. It has a glass plate swiveling right and left. The apparatus was equipped with a digital control system for irradiation time and microwave power; the latter was linearly adjustable from 100 to 1,000 W. Drying experiments were conducted at different temperatures: 40, 80, and 120°C and at different microwave powers: 100, 500, and 1,000 W. During drying trials, 10 g of sample were uniformly spread as a thin layer, and their moisture loss was measured by weighing on the digital balance with a precision of 0.01 g (RADWAG, WPS 600/C/2, Poland). Drying processes were continued until the sample weight reached a constant weight. All experiments were performed in triplicate.

2.3 | Drying rate

When a new drying process has to be used, or if another type of food has to be dried, some experimentation is required to find the DR. The latter has a significant effect on the quality of the dried food (in artificial dryers) and fuel consumption. This parameter can be calculated as follows:

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (1)$$

where DR is the drying rate, M_{t+dt} and M_t are moistures content at $t + dt$ and t , respectively, and dt is the time difference.

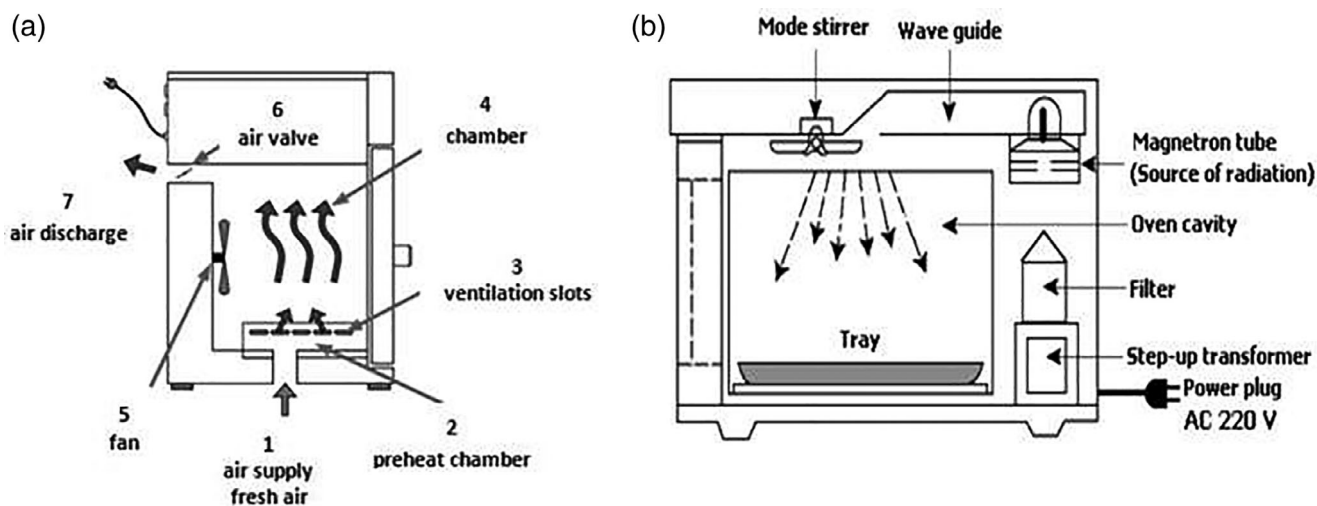


FIGURE 1 Schematic of the dryers: (a) Conventional oven and (b) microwave oven

2.4 | Mathematical modeling of drying curves

In this study, 23 thin-layer drying equations summarized in Table 1 were tested for modeling to obtain the best model describing the drying behavior of coriander leaves. All these models estimate that the drying curves answer to an equation of the moisture ratio versus drying time. Dimensionless moisture ratio (MR) was computed as follows:

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

where MR is the moisture ratio, M_t is moisture content at a specific time t ; M_0 and M_e are initial and equilibrium moisture content, respectively.

Since the M_e values are relatively insignificant when compared with M_t or M_0 , it can therefore be set to zero, thus the MR can be simplified to Equation (3) (Darvishi et al., 2014):

$$MR = \frac{M_t}{M_0} \quad (3)$$

Modeling the drying behavior of diverse products often needs the statistical methods of regression and correlation analysis (Akpınar, 2006). That is why a nonlinear regression analysis was conducted using a Statistica software (version 8), and the goodness of fit of the tested models to the experimental data was evaluated and compared using three statistical parameters, namely adjusted determination coefficient (adjusted R^2), chi-square (χ^2), and root mean square error (RMSE):

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{N - z} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{N}} \quad (5)$$

where $MR_{exp,i}$ and $MR_{pre,i}$ are, respectively, the experimental and predicted moisture ratio, N is the number of observations, and z is the number of constant parameters in the model equation.

TABLE 1 Mathematical models given by various authors for drying curves

Model name	Mathematical equation
Newton	$MR = \exp(-kt)$
Henderson and Pabis	$MR = a \cdot \exp(-kt)$
Logarithmic	$MR = a \cdot \exp(-kt) + c$
Page	$MR = \exp(-kt^n)$
Modified page 1	$MR = \exp(-[kt]^n)$
Modified page 2	$MR = \exp(-kt^n)$
Midilli et al.	$MR = a \cdot \exp(-kt^n) + bt$
Two terms	$MR = a \cdot \exp(-kt) + b \cdot \exp(-k_1t)$
Two terms exponential	$MR = a \cdot \exp(-kt) + (1-a) \cdot \exp(-kat)$
Approximation of diffusion	$MR = a \cdot \exp(-kt) + (1-a) \cdot \exp(-kbt)$
Verma et al.	$MR = a \cdot \exp(-kt) + (1-a) \cdot \exp(-k_1t)$
Modified Henderson and Pabis	$MR = a \cdot \exp(-kt) + b \cdot \exp(-k_1t) + c \cdot \exp(-k_2t)$
Parabolic	$MR = a + b \cdot t + c \cdot t^2$
Wang and Singh	$MR = 1 + a \cdot t + b \cdot t^2$
Chavez-Mendez et al.	$MR = (1 - [1 - L_2]L_1t)^{1/(1-L_2)}$
Logistic	$MR = b / (1 + a \cdot \exp[k \cdot t])$
Sledz et al.	$MR = b \cdot \exp(-kt) / (1 + a \cdot \exp[k_1 \cdot t])$
Simplified Fick's diffusion equation	$MR = a \cdot \exp(-k[t/L^2])$
Weibull	$MR = \exp(-[t/a]^b)$
Demir et al.	$MR = a \cdot \exp(-kt)^n + b$
Taghian Dinani et al.	$MR = a \cdot \exp(-([t-b]/a)^2)$
Fernando and Amarasinghe	$MR = (1 + a \cdot t + b \cdot t^2) / (1 + c \cdot t)$
Hii et al.	$MR = a \cdot \exp(-kt^n) + c \cdot \exp(-gt^n)$

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

2.5 | Effective moisture diffusivity determination

Diffusion into solids during drying is a complex process that can involve several phenomena, such as molecular diffusion, capillary flow, Knudsen flow, hydrodynamic flow, or surface diffusion. All these phenomena are combined in one term named as effective moisture diffusivity (D_{eff}) (Erbay & Icier, 2010). For sheet material, the effective moisture diffusivity is calculated as follows (Demirhan & Özbek, 2011):

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{\left(\frac{-(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right)} \quad (6)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), L is the half thickness (drying from both sides) of coriander leaves ($L = 0.00015$ m), n is the positive integer, and t is drying time (s).

For longer drying period, the abovementioned equation can be further simplified to only the first term of series and can be written in a logarithmic form as follows (Kumar, Sarkar, & Sharma, 2011):

$$\ln(MR) = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \quad (7)$$

The above equation is assessed numerically for Fourier number, $F_0 = D_{eff} \cdot t / L^2$ (Darvishi et al., 2014), for this, Equation (7) can be rewritten as follows:

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

Thus,

$$F_0 = -0.101 \ln(MR) - 0.0213 \quad (9)$$

Effective moisture diffusivity was calculated as follows:

$$D_{\text{eff}} = \frac{F_0}{\left(\frac{t}{4L^2}\right)} = \frac{-0.101 \ln(MR) - 0.0213}{\left(\frac{t}{4L^2}\right)} \quad (10)$$

2.6 | Energy consumption

Energy consumption can be evaluated using two different efficiency indices, namely specific electrical energy consumption (Equation 11) or EE (Equation 12) (Tsotsas & Mujumdar, 2014):

$$\text{SEC}_e = \frac{3600E}{M_s(X_i - X_f)} \quad (11)$$

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 final moisture contents (dm), respectively, and M_s is the mass of dry solid matter (in kg).

$$\text{EE} = M_s(X_i - X_f) \frac{\Delta h_v}{3600E} \cdot 100 \quad (12)$$

where EE is the energy efficiency (%) and Δh_v is the evaporation enthalpy of water (2,257 kJ/kg, at 100°C).

2.7 | Phytochemical quality

2.7.1 | Total phenolic compounds extraction and determination

Total phenolic compounds were extracted using the method of Zielinska, Zielinska, and Markowski (2017) with some modifications. Briefly, the TPCs were extracted from a test portion of approx. 0.05 g of each sample by sonication for 30 s with 1 mL ethanol-water 50% (50/50: vol/vol). The mixture was vortexed for 30 s, repeatedly sonicated, vortexed, and centrifuged for 10 min (13,200g). This step was repeated five times on the residue with another 1 mL of solvent. The supernatants were then collected in a 5 mL vial and stored in the refrigerator. The extraction procedure was conducted in triplicate. Then, the polyphenol content was quantified using the Folin-Ciocalteu reagent, with reference to the method described by Georgé, Brat, Alter, and Amiot (2005), briefly, 2.5 mL of Folin-Ciocalteu

reagent (diluted 10 times 1/10) were added to the extracts. The mixture was incubated for 2 min at room temperature, and 2 mL of saturated sodium carbonate solution (75 g/L) were added. The solution was incubated for 15 min at 50°C and finally cooled in a water-ice bath. The specific absorbance at 760 nm was immediately measured by a spectrophotometer (UV-mini 1240, Shimadzu, Japan), and the TPC was expressed as milligram gallic acid equivalents per milliliter (mg GAE/mL).

2.7.2 | Antioxidant activity determination

Anti-free radical activity estimation of extracts has been measured by two tests: ABTs and DPPH.

ABTs test was achieved according to Re et al. (1999) method; it consists of dissolving ABTS in water to a concentration of 7 mM, followed by the production of the radical cation ABTS (ABTS^+) by reacting the stock solution of ABTS with 2.45 mM potassium persulfate and allowing the mixture to stand in the dark for 12–16 hrs before use. Before use, the ABTS^+ solution was diluted with ethanol to an absorbance of 0.700 ± 0.050 at 734 nm, then 1 mL was added to 0.01 mL of 1:5 diluted extract. After 6 min of incubation in the dark, the absorbance was measured at 734 nm. All determinations were performed in triplicate, and the result is expressed in terms of percent inhibition calculated with reference to the following equation:

$$\% \text{Inhibition} = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100 \quad (13)$$

where, A_{control} was the absorbance of the ABTS^+ solution without any antioxidant, A_{sample} was the absorbance of ABTS^+ solution after reaction with the extract.

DPPH test was realized according to Achat et al. (2012) method. Briefly, 1 mL of each ethanolic extract solution of the different dried powders was added to 2 mL of DPPH solution (2×10^4 mol/L in methanol), and the mixture was left in the dark at room temperature for 30 min, then the absorbance was measured at 517 nm. All experiments were performed in triplicate, and the result was expressed in terms of percent inhibition calculated using the following equation:

$$\% \text{Inhibition} = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100 \quad (14)$$

where, A_{control} was the absorbance of DPPH solution without any antioxidant, A_{sample} was the absorbance of DPPH solution after reaction with the extract.

2.8 | Statistical analysis

All experiments were completed in triplicate, and the experimental data were expressed as means $\pm$ standard deviation. The statistical comparisons were performed using analysis of variance (ANOVA)

using JMP pro 10 software. The significance of the differences between the means is determined by the Tukey test at $p \leq .05$. PCA (XLSTAT Version May 3, 2014) was performed to visualize the correlation between kinetic parameters, energy consumption, and phytochemical quality of coriander samples dried by both processes.

3 | RESULTS AND DISCUSSION

3.1 | Graphical representations of drying kinetics

3.1.1 | Variation of moisture content versus time

The mass losses of the samples during the two applied processes, convective and microwave drying, are presented as drying curves (Figure 2a,b, respectively). As shown in these figures and for various applied drying conditions, the MR decreased as the drying time increased. The drying curves thus presented a similar pattern to that obtained for other plant materials, indicating a rapid removal of moisture from the product at the initial stage, which then decreases with increasing drying time (Bishnoi, Chhikara, Singhania, & Ray, 2020; Hidar et al., 2020). Nevertheless, the continuous reduction in water content indicates that diffusion governs the internal mass transfer (Tarafdar et al., 2021).

Looking at the same figures (Figure 2a,b), it is also clear that the drying temperature and power level have a significant effect on the

total drying time. Hence, the time involved to achieve the final moisture content for drying was variable and is in the order of 290.67, 22.67, and 8.06 min for temperatures ranging from 40 to 120°C and were in the order of 46.17, 5.94, and 2.53 min for powers ranging from 100 to 1,000 W (Table 3). Thus, as we move from low temperature and power levels to high levels, water loss occurs more quickly than at the previous level. Previous reports support the result observed in this study, including work done by Abbaspour-Gilandeh, Jahanbakhshi, and Kaveh (2019), Cherrat, Boulkebach-Makhlouf, Zeghichi, and Walker (2019), Felizardo, Merlo, and Maia (2021), Jia et al. (2019), Keneni, Hvoslef-Eide, and Marchetti (2019), Wu, Zhang, and Li (2019), Macedo, Vimercati, Araújo, Saraiva, and Teixeira (2020), Hnin et al. (2021), who studied convective drying and those of Alibas, Zia, and Yilmaz (2019), Keskin et al. (2019) and Kouhila et al. (2020), who studied microwave drying process.

Furthermore, the comparison of the two drying processes, convective and microwave based on the corresponding drying time results for each temperature and power (Table 3), showed that microwave drying allows a significant reduction in time, especially when high power levels were applied (500 and 1,000 W). Similar results were reported by Ali et al. (2020), Miccio, Pierri, Cuccurullo, Metallo, and Brachi (2020), and Mouhoubi et al. (2020). Such a result could be explained by the fact that one of the advantages of microwave drying is the short processing time (Amiri Chayjan, Kaveh, & Khayati, 2015).

3.1.2 | Variation of drying rate versus moisture content

Figure 3a,b illustrates the variation in DR versus moisture content during convective and microwave drying processes, respectively.

During convective drying (Figure 3a), whatever the drying temperature applied, the moisture loss was faster at the beginning of the drying process than at the end. As for microwave drying (Figure 3b), the application of 100 W power led to the observation of the same trend observed during convective drying, while at particularly high powers (500 and 1,000 W), the trend is different because an increase in DR was first observed, which are then followed by a decrease. The possible explanation for the high DR at the beginning that decreases at the end of the drying process is that the water content in the sample to be dried is relatively high in the first step of the drying process, resulting in greater diffusion of moisture. As the drying process progressed, a decrease in absorption occurred due to a decrease in the moisture content of the product, resulting in a decrease in the DR (Alibas & Kacar, 2016; Arslan & Musa Özcan, 2010).

It has also been observed that at higher moisture content, the highest DRs were induced when the temperature or microwave power was increased. Thus, the average drying rate was variable from 0.03 to 1.01 kg water/kg dm min and from 0.16 to 3.08 kg water/kg dm min during convective and microwave drying, respectively. These results are congruent with those reported in the literature on both convective drying and microwave drying (Alibas & Kacar, 2016; Alibas, Zia, & Yilmaz, 2019).

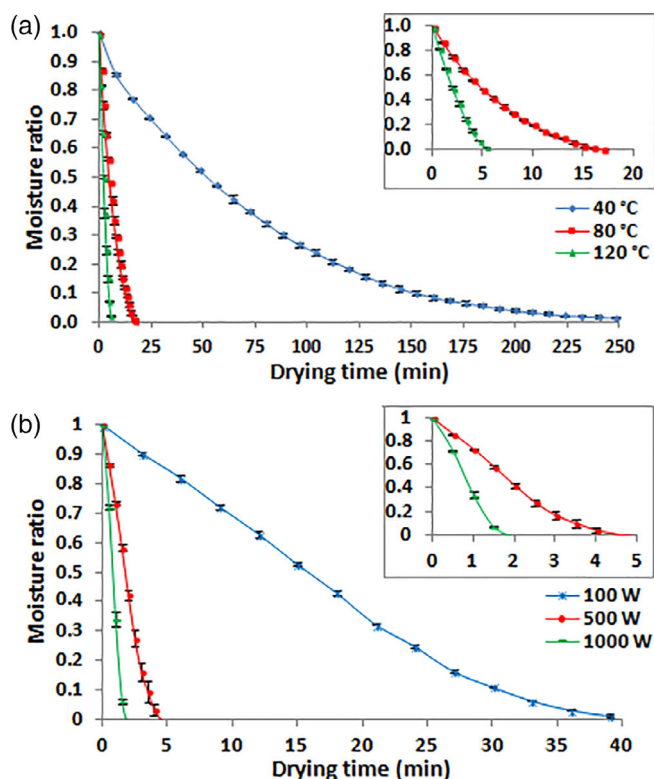


FIGURE 2 Moisture ratio profiles of coriander leaves during: (a) Convective drying and (b) microwave drying

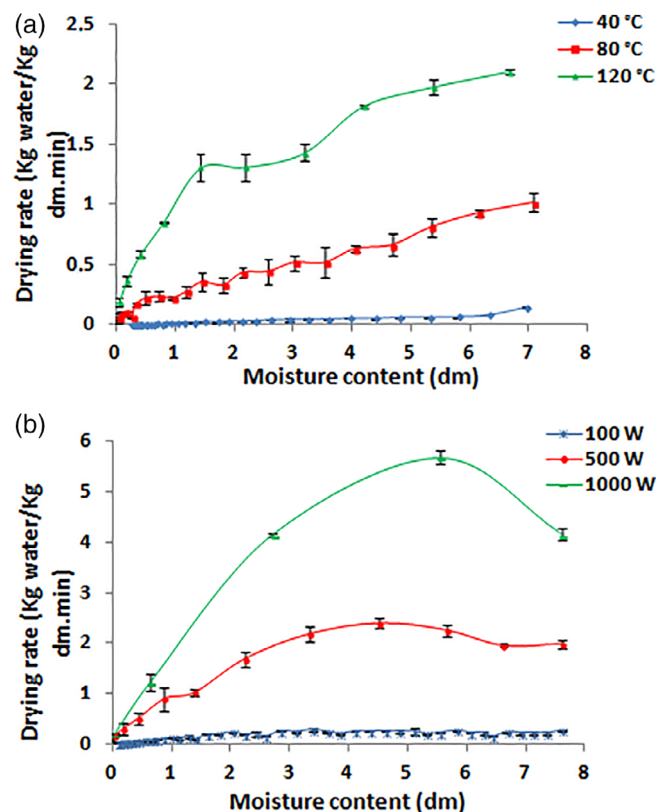


FIGURE 3 Variations of drying rate versus moisture content during: (a) Convective drying and (b) microwave drying

As a comparison of the two processes, statistical analysis illustrated in Table 3 showed that the most important drying rates were induced by applying the microwave drying process, especially when applying powers of 500 and 1,000 W. This can be explained by the fact that microwaves have the advantage of reducing the drying time due to the rapid absorption of energy by water molecules, thus causing their rapid evaporation, resulting in high drying rates (Doymaz et al., 2016).

3.2 | Drying kinetics modeling

The MR data obtained during the drying tests were adjusted to the data of the 23 empirical models, listed in Table 1, and the results were evaluated on the basis of those of the statistical parameters: adjusted determination coefficient (R^2), chi-square (χ^2), and root mean square error (RMSE). The high adjusted R^2 values and the low χ^2 and the RMSE values refer in all cases to good adequacy of the model (Kaveh & Amiri Chayjan, 2017). At the end of the nonlinear regression analysis of the 23 models considered in this study, five models, namely, Midilli et al., Logistic, Sledz et al., Taghian Dinani et al., Hii et al., whose results of their drying constants and coefficients as well as their statistical parameters are shown in Table 2 for both convective and microwave drying, gave high adjusted R^2 values and the lowest χ^2 and RMSE values. These models then

seem to be the most appropriate to describe the drying processes of coriander leaves under the experimental conditions studied. However, the Sledz et al. model gave comparatively higher adjusted R^2 values in all cases, while χ^2 and RMSE values were lower (it is determined that adjusted R^2 , χ^2 , and RMSE ranged from .9991 to .9995, from 0.0001 to 0.0005, and from 0.0070 to 0.0228, respectively). It can therefore be assumed that this model better characterizes the drying behavior of coriander leaves in both convective and microwave drying. More particularly as in the present study, other authors have obtained good results when applying this model in drying kinetics of food sheets: Sledz, Wiktor, Rybak, Nowacka, and Witrowa-Rajchert (2016) who have studied the parsley leaves drying and Sledz et al. (2017) who have studied the basil leaves drying.

3.3 | Effective moisture diffusivity

The average values of the effective diffusivities involved during the two drying processes of coriander leaves are illustrated in Table 3. Indeed, when shifting from the lowest temperatures or power levels to the highest ones, D_{eff} values show a variation ranging from 0.02×10^{-10} to 0.44×10^{-10} m²/s and from 0.05×10^{-10} to 1.21×10^{-10} m²/s for convective and microwave assisted drying, respectively. For the two processes studied, the D_{eff} values obtained fall within the general range defined by Kaveh, Jahanbakhshi, Abbaspour-Gilandeh, Taghinezhad, and Moghimi (2018), which is 10^{-12} to 10^{-8} m²/s for agricultural and food products. These values are also comparable to the values published for food sheets, more particularly as in the present study: for example, *Allium roseum* leaves (Ben Haj Said, Najjaa, Farhat, Neffati, & Bellagha, 2014), rosemary leaves (Bensebia & Allia, 2015), celery leaves (Demirhan & Özbek, 2011; Mouhoubi et al., 2020), kaffir lime leaves (Tasirin, Puspasari, Lun, Chai, & Lee, 2014), peppermint (Arslan, Özcan, & Mengeş, 2010), *Piper umbellatum* L. leaves (Dorneles et al., 2019), and *Moringa olifera* leaves (Tarafdar et al., 2021).

Statistical analysis of D_{eff} values for both drying processes revealed that the values obtained at 40 and 80°C are not statistically different from that obtained at 100 W. The value obtained at 120°C is not statistically different from that obtained at 500 W. However, at 1000 W, the D_{eff} value is higher and is not comparable to the D_{eff} values of the convective process.

3.4 | Energy consumption

Drying is an energy-intensive process, and the magnitude of applied energy is important because of energy costs (Balbay & Şahin, 2012). Thiery et al. (2016) have reported that globally, industrial drying represents 9% of the total energy consumption. In turn, Alibas and Kacar (2016) have reported that drying represents 30–50% of the total costs in medicinal plant production. Hence, predicting the energy invested during a sample drying process could greatly benefit these

TABLE 2 The values of the drying constants and coefficients and the statistical parameters for the best models

								Statistical parameters		
Model	Drying conditions		The drying constants and coefficients					Adjusted R ²	χ ²	RMSE
Midilli et al.	CD	40°C	$a = 0.9283$	$k = 0.0070$	$n = 1.1334$	$b = -0.0001$		.9988	0.0001	0.0089
		80°C	$a = 0.9855$	$k = 0.1185$	$n = 1.0665$	$b = -0.0050$		.9989	0.0001	0.0092
		120°C	$a = 0.9634$	$k = 0.2372$	$n = 1.3409$	$b = -0.0137$		.9983	0.0002	0.0124
	MD	100 W	$a = 0.9520$	$k = 0.0066$	$n = 1.6438$	$b = -0.0014$		.9988	0.0001	0.0109
		500 W	$a = 0.9318$	$k = 0.2158$	$n = 1.7195$	$b = -0.0132$		.9944	0.0006	0.0235
		1,000 W	$a = 0.9569$	$k = 1.0010$	$n = 1.9585$	$b = -0.0228$		.9976	0.0003	0.0165
Logistic	CD	40°C	$b = 2.0106$	$a = 1.1655$	$k = 0.0182$			.9988	0.0001	0.0092
		80°C	$b = 1.5611$	$a = 0.6286$	$k = 0.2488$			.9959	0.0004	0.0191
		120°C	$b = 1.1903$	$a = 0.2477$	$k = 0.8449$			.9961	0.0004	0.0199
	MD	100 W	$b = 1.0820$	$a = 0.1324$	$k = 0.1386$			.9979	0.0002	0.0156
		500 W	$b = 1.0414$	$a = 0.1121$	$k = 1.2687$			.9935	0.0007	0.0258
		1,000 W	$b = 1.0349$	$a = 0.0729$	$k = 3.4273$			.9967	0.0004	0.0203
Sledz et al.	CD	40°C	$b = 1.0158$	$k = 0.0105$	$a = 0.0730$	$k_1 = 0.0171$		.9992	0.0001	0.0071
		80°C	$b = 1.0053$	$k = 0.1427$	$a = 0.0013$	$k_1 = 0.4998$		.9992	0.0001	0.0081
		120°C	$b = 1.0161$	$k = 0.3058$	$a = 0.0065$	$k_1 = 1.2782$		.9991	0.0001	0.0089
	MD	100 W	$b = 1.0191$	$k = 0.0293$	$a = 0.0184$	$k_1 = 0.1702$		.9995	0.0001	0.0070
		500 W	$b = 0.9986$	$k = 0.2193$	$a = 0.0231$	$k_1 = 1.4873$		.9947	0.0005	0.0228
		1,000 W	$b = 1.0269$	$k = 0.5099$	$a = 0.0133$	$k_1 = 4.1429$		.9982	0.0002	0.0146
Taghian Dinani et al.	CD	40°C	$a = 3.1102$	$b = -221.6170$	$c = 202.4278$			.9991	0.0001	0.0076
		80°C	$a = 1.5537$	$b = -8.9319$	$c = 12.9796$			.9972	0.0002	0.0156
		120°C	$a = 1.0608$	$b = -1.1410$	$c = 3.64855$			.9973	0.0003	0.0165
	MD	100 W	$a = 0.9690$	$b = -2.7712$	$c = 22.5085$			.9983	0.0002	0.0141
		500 W	$a = 0.9366$	$b = -0.1903$	$c = 2.4721$			.9936	0.0007	0.0255
		1,000 W	$a = 0.9507$	$b = 0.0168$	$c = 0.9421$			.9965	0.0010	0.0306
Hii et al.	CD	40°C	$a = 0.2724$	$k = 0.0054$	$n = 1.1937$	$c = 0.6427$	$g = 0.0054$	.9985	0.0001	0.0102
		80°C	$a = 0.2583$	$k = 0.2507$	$n = 1.8879$	$c = 0.6946$	$g = 0.0167$	.9984	0.0001	0.0115
		120°C	$a = 0.4787$	$k = 0.2007$	$n = 1.6046$	$c = 0.4502$	$g = 0.2007$	.9956	0.0005	0.0207
	MD	100 W	$a = 2.2639$	$k = 0.0087$	$n = 1.6787$	$c = -1.3265$	$g = 0.0109$	.9979	0.0002	0.0152
		500 W	$a = -2.9367$	$k = 0.1332$	$n = 1.6336$	$c = 3.8705$	$g = 0.1574$	.9945	0.0006	0.0232
		1,000 W	$a = 0.4712$	$k = 1.0760$	$n = 2.1279$	$c = 0.4712$	$g = 1.0760$	.9966	0.0010	0.0291

Note: Bold values indicate that the highest R² values and the lowest X² and RMSE values which correspond and refer directly to the best model chosen.

Abbreviations: CD, convective drying; MD, microwave drying.

industries so that they can choose the process that consumes less energy and, therefore, reduce costs.

The energy consumed during each of the two drying processes and under the different levels applied for each of them was evaluated by calculating two indices: SEC_e and EE (Table 3). The results indicate that as the drying air temperature or microwave power increases, the SEC_e values decrease and the EE values increase. The SEC_e values, therefore, range from $7.63 \times 10^{+7}$ to $208.33 \times 10^{+7}$ MJ/kg for convective drying and from $1.86 \times 10^{+7}$ to $29.48 \times 10^{+7}$ MJ/kg for microwave one. In turn, the EE values range from 0.11×10^{-3} to $3.12 \times 10^{-3}\%$ and from 0.77×10^{-3} to $12.16 \times 10^{-3}\%$, in the same order. This implies an inverse relationship between these two indices: SEC_e and EE, thus confirming the result reported by Tsotsas and

Mujumdar (2014), Kaveh et al. (2021) and Maftoonazad, Dehghani, and Ramaswamy (2020).

Many researchers have reported the decrease of SEC_e values when increasing the air temperature (Abbaspour-Gilandeh, Jahanbakhshi, & Kaveh, 2019; Jahanbakhshi, Yeganeh, & Momeny, 2020; Motevali & Tabatabaee Koloor, 2017). This suggests that increasing the temperature would decrease the consumption of energy by virtue of reduced drying times (Tarafdar et al., 2021). That is, by increasing the temperature, the drying time and SEC_e were reduced because the thermal gradient and the acceleration of moisture extraction were improved (Kaveh, Amiri Chayjan, Taghinezhad, Rasooli Sharabiani, & Motevali, 2020).

Another study also proved the decrease in this energy by increasing microwave power levels (Jahanbakhshi, Kaveh, et al., 2020), and

TABLE 3 Statistical analysis result of kinetic parameters (time, DR and D_{eff}), energy consumption (SEC_e and EE), and phytochemical quality (TPC, ABTs, and DPPH)

	Convective drying			Microwave drying		
	40°C	80°C	120°C	100 W	500 W	1,000 W
Time (min)	290.67 ± 2.31 ^A	22.67 ± 0.29 ^C	8.06 ± 0.19 ^D	46.17 ± 0.29 ^B	5.94 ± 0.10 ^D	2.53 ± 0.05 ^E
DR (kg water/kg dm min)	0.03 ± 0.00 ^F	0.35 ± 0.00 ^D	1.01 ± 0.00 ^C	0.16 ± 0.00 ^E	1.29 ± 0.00 ^B	3.08 ± 0.00 ^A
D_{eff} ($\times 10^{-10}$ m ² /s)	0.02 ± 0.00 ^C	0.18 ± 0.00 ^C	0.44 ± 0.02 ^B	0.05 ± 0.00 ^C	0.46 ± 0.04 ^B	1.21 ± 0.20 ^A
SEC_e ($\times 10^{-07}$ MJ/kg H ₂ O)	208.33 ± 1.96 ^A	20.68 ± 0.37 ^C	7.63 ± 0.31 ^D	29.48 ± 0.65 ^B	4.39 ± 0.08 ^E	1.86 ± 0.02 ^F
EE ($\times 10^{-03}$ %)	0.11 ± 0.00 ^F	1.15 ± 0.02 ^D	3.12 ± 0.13 ^C	0.77 ± 0.02 ^E	5.14 ± 0.09 ^B	12.16 ± 0.11 ^A
TPC (mg GAE/mL)	0.31 ± 0.02 ^A	0.10 ± 0.00 ^D	0.20 ± 0.00 ^{BC}	0.14 ± 0.01 ^{CD}	0.24 ± 0.02 ^B	0.37 ± 0.027 ^A
ABTs (%)	82.57 ± 0.52 ^A	35.16 ± 0.31 ^D	70.28 ± 0.96 ^B	44.99 ± 0.88 ^C	81.84 ± 0.43 ^A	83.33 ± 0.24 ^A
DPPH (%)	69.30 ± 0.51 ^{BC}	66.66 ± 0.57 ^D	67.20 ± 0.79 ^{CD}	61.21 ± 1.33 ^E	70.06 ± 0.41 ^B	71.94 ± 0.33 ^A

Note: Table shows mean (M) values with standard deviation (SD) of the mean. Same index letters in ROW indicate no significant difference.

having suggested that the highly effective moisture diffusivity in using high power microwaves due to changes in cellular structure results in faster moisture release and reduced drying time and hence reduced energy consumption.

Statistical analysis of the SEC_e values obtained for the two drying processes demonstrated that the most important SEC_e values are obtained when drying at low temperatures (40 and 80°C) and at the lowest power (100 W), which are statistically different from each other. The lowest SEC_e values obtained for powers of 500 and 1,000 W are all statistically different from the values obtained during convective drying and from each other.

Statistical analysis of the EE values obtained for both drying processes showed that the lowest value is induced at low temperature (40°C), which is statistically different from the values obtained for all other temperatures or microwave power. While the highest values are obtained at high powers (500 and 1,000 W) and these are statistically also different from each other.

Therefore, in view of the above, the comparison between the two drying processes applied in terms of energy consumption has shown that convective drying consumes more energy than the microwave process, while the latter has higher EE.

3.5 | Total phenolic contents (TPC)

The result of total phenolic content (TPC) determination of coriander leaves dried at different convective drying temperatures and microwave powers are presented in Table 3.

The TPC is 0.31 mg GAE/mL after heat treatment at 40°C; it decreases to a value of 0.10 mg GAE/mL at 80°C and increases again at 120°C (0.20 mg GAE/mL). Similar results were obtained by Nguyen, Van Vuong, Bowyer, Van Altena, and Scarlett (2015) who studied the effect of drying at 80, 100, and 120°C on the bioactive compounds of *Phyllanthus amarus*.

After heat treatment at 120°C, the TPC was increased to 0.20 mg GAE/mL. This increase could be attributed to the formation of Maillard reaction products that lead to the formation of novel

phenolic compounds at high temperature (Que, Mao, Fang, & Wu, 2008). In addition, it can be assumed that higher molecular weight bound phenolic compounds present in coriander may have been released in simple free forms by heat treatment, thus increasing the TPC of the samples (Bushra, 2012).

The microwave significantly affected the TPC; in fact, it increased with power, with a value of 0.14 mg GAE/mL at 100 W followed by 0.24 mg GAE/mL at 500 W to reach the highest content at 1000 W of 0.37 mg GAE/mL. This can be explained by the intense heat generated by the microwaves, which create a high vapor pressure and temperature inside the plant tissues, which increases with the rise of the microwave power, which disturbs the polymers of the plant cell walls. As a result, phenolic compounds from the cell wall or bound phenolic compounds may be released, resulting in the extraction of more phenolic compounds (Hamrouni-Sellami et al., 2012).

According to the results of the TPC assay, the levels obtained after microwave drying are significantly higher than those obtained from oven-dried powders (Table 3). The best TPC was obtained for coriander dried at 1000 W. The lowest contents were obtained after oven drying at 80°C. These results are in agreement with those reported in the literature (Chang, Lin, Chang, & Liu, 2006; Gao, Wu, Wang, Xu, & Du, 2012). A possible explanation for this result is that the faster heating phenomena of microwave drying deactivate the polyphenol oxidases more quickly than convective drying, thus delaying the enzymatic deterioration of the polyphenols (Sarkar, Salauddin, Hazra, & Chakraborty, 2020).

3.6 | Antioxidant activity

Antioxidant activity of coriander powders obtained after convection and microwave drying was evaluated by two antiradical tests: ABTs and DPPH (Table 3).

The ABTs and DPPH inhibition percentages of dried coriander at 40°C are 82.57 and 69.30%, then decrease to 35.16 and 66.66% values at 80°C, increasing again at 120°C to 70.28 and 67.20%, respectively. This indicates that temperature influences antioxidant

activity in a variable way. Similar results were achieved by Nguyen et al. (2015). Indeed, at high temperature (120°C), there is production and accumulation of Maillard-derived melanoids with a variable degree of antioxidant activity that could also improve antioxidant properties (Vega-Gálvez et al., 2009). It is also hypothesized that the drying process could perturb the cell wall and release antioxidant compounds, thus increasing the supply of bio-accessible antioxidant compounds (Choi, Lee, Chun, Lee, & Lee, 2006; Zannou, Pashazadeh, Ghellam, Hassan, & Koca, 2021).

The ABTs and DPPH inhibition percentages for coriander dried in microwaves at 100, 500, and 1,000 W are 44.99, 81.84, and 83.33% for ABTs and 61.21, 70.06, and 71.94% for DPPH, respectively. The percentages increase as the power increases, a result consistent with that obtained by Hamrouni-Sellami et al. (2012), who found that, as the microwave drying power increases from 600 to 800 W, the antioxidant activity of sage increases.

According to the obtained results (Table 3), inhibition percentages after microwave drying are substantially higher than those achieved after convective drying. Hence, the best ABTs and DPPH inhibition percentages were obtained for coriander dried at 1,000 W (83.326 and 71.938%, respectively), while the lowest values were obtained for coriander dried at 80°C.

3.7 | Principal component analysis (PCA)

To better understand the interactions between kinetic parameters (DR and D_{eff}), energy consumption (SEC_e and EE), and phytochemical quality (TPC, DPPH, and ABTs) of coriander samples dried by the two processes, convective and microwave, the implementation of PCA could be an interesting solution. The resulting PCA model explains 93.41% of the variability in the analyzed data: Component 1 (PC1, Figure 4) of the PCA accounted for 66.80% of the variance and was expressed mainly by drying rate (DR), effective diffusivities (D_{eff}), energy efficiency (EE), total polyphenol content (TPC), DPPH, and ABTs, which had good correlations between them. While component 2 (PC2, Figure 4), which accounted for 26.61% of the variance, is exclusively represented by electrical specific energy consumption (SEC_e).

The PCA results (Figure 4) showed that there was a very significant correlation between the kinetic parameters each other and with energy consumption, namely, between drying rate (DR) and effective diffusivity (D_{eff}) ($r = .99$), between drying rate (DR) and energy efficiency (EE) ($r = .99$), and between effective diffusivity (D_{eff}) and energy efficiency (EE) ($r = .99$).

It has also been shown that the TPC correlates with antioxidant activity, whether with DPPH ($r = .79$) or ABTs ($r = .90$). Similar results have been found by many researchers, namely, Zhao, Yang, Wang, and Lu (2009), Bushra (2012), Lim, Pang, Yusoff, Mudalip, and Gimbin (2019), and Himed-Idir et al. (2021). Nevertheless, Zheng and Wang (2001) suggested that not only the level of antioxidants but also a synergy between them and other plant constituents could influence the difference in the antioxidant capacity of plant extracts. This may

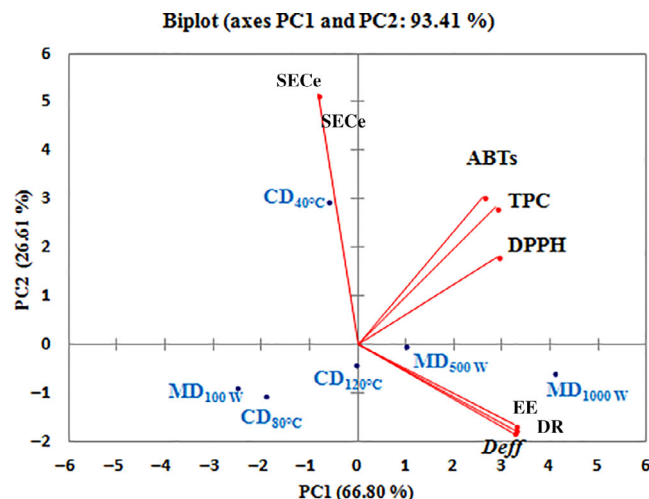


FIGURE 4 Biplot illustrating the relationship between kinetic parameters, energy consumption, and phytochemical quality of coriander. CD, convective drying; D_{eff} , effective moisture diffusivity; DR, drying rate; EE, energy efficiency; MD, microwave drying; SEC_e , specific electrical energy consumption; TPC, total phenolic compounds

explain why even samples having similar concentrations of total phenolics can vary remarkably in their antioxidant activity due to the synergistic and antagonistic interactions between antioxidants (Terpinc, Čeh, Ulrih, & Abramovič, 2012).

4 | CONCLUSIONS

The drying behavior of coriander leaves was investigated over three drying air temperatures in a conventional dryer (40, 80, and 120°C) and three microwave power levels (100, 500, and 1,000 W). It was found that a significant reduction in time and high drying rates and diffusivities were induced by the application of a microwave dryer. Thus, the minimum time and maximum DR and D_{eff} values were calculated at 2.53 min, 3.08 kg water/kg dm min, and 1.21×10^{-10} m²/s, respectively. Among the models used to predict the MR of coriander leaves, Sledz model has proven to be the best model with adjusted $R^2 \geq .9947$. The maximum SEC_e and EE values were, respectively, $208.33 \times 10^{+07}$ MJ/kg H₂O and $12.16 \times 10^{-03}\%$, which were obtained at the air temperature of 40°C and at a microwave power of 1,000 W, in the same respective order. Regarding the phytochemical quality, the results showed that the highest TPC (0.37 mg GAE/mL) and the best antioxidant activities, 83.33 and 71.94% for ABTs and DPPH, respectively, were obtained during drying in the microwave dryer.

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CONFLICT OF INTEREST

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

AUTHOR CONTRIBUTIONS

Khokha Mouhoubi: Investigation, Writing-original draft; **Lila Boulekbache-Makhlouf:** Validation, Writing-review and editing; **Wafa Mehaba:** Investigation; **Hayat Himed-Idir:** Validation; **Khodir Madani:** Methodology, Supervision.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

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