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Mathematical modelling of thin-layer drying kinetics of *Matricaria pubescens* leaves

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Abstract

Medicinal plants are generally harvested with a high-water content. It is therefore essential to dry them as quickly as possible to prevent degradation before use. Most compounds in medicinal plants are sensitive to drying, so it is important to adjust the drying conditions. This study aimed to describe the drying of *Matricaria pubescens* leaves, select the most suitable models for each drying condition, and determine the activation energy and thermodynamic properties. The leaves were harvested with a water content of 4% ($\pm 0.3\%$, dry basis). The drying experiments were conducted at three drying air temperatures (30°C, 40°C, and 50°C), and for three air velocities (0.5 m/s, 1 m/s, and 1.5 m/s). The Midilli and Kucuk model was selected as the most appropriate for predicting the drying characteristics of *Matricaria pubescens* leaves. The calculated water diffusivities ranged from 1.58×10^{-11} to 1.58×10^{-11} m²/s. A relatively high activation energy of 80.18 kJ/mol was observed at low air velocity, indicating that the drying kinetics are strongly temperature-dependent.

Introduction

Matricaria pubescens (Desf.) Sch.Bip., known as "El Ouazouaza," is a Saharan medicinal plant from the Asteraceae family, which is mainly distributed in arid and semi-arid areas. This plant has been used in folk medicine for the management of several diseases, including digestive, respiratory, and infectious diseases. Researchers have also evaluated its clinical use for other purposes, most notably for the treatment of rheumatism, inflammation, diabetes, and hypertension (Amssayef A and Eddouks M. 2019; H. Chenna et al, 2024; Mohammed Tahar Ben Moussa et al, 2020; Amssayef A et al, 2020).

Matricaria pubescens has been reported for its considerable phytochemical composition, including polyphenols, flavonoids, and condensed tannins. The extracts of *Matricaria pubescens* displayed antioxidant and antidiabetic effects (Metrouh-Amir, H., & Amir, N. 2018; Abdelhadi, I., 2025).

The extracts of *Matricaria pubescens* also demonstrated antibacterial activity against several bacterial species (Elhasnaoui A et al., 2025). Some studies have also alluded to some clinical applications of the plant for the treatment of hypertension. One study involving aqueous extract of the aerial portion of *Matricaria pubescens* demonstrated an antihypertensive effect in L-NAME-induced hypertensive rats via a vasodilatory mechanism. Additionally, other studies have evaluated the antihyperglycemic properties of *Matricaria pubescens* (K. Kherraz, 2019; Benmoussa, M.T., 2022).

Drying is an essential process for reducing water content in plant material to minimize microbial contamination (bacteria, molds) and the activity of enzymes that could lead to the deterioration

of bioactive compounds (Tran and Hoang, 2025; Wu et al., 2025). Incorrect drying techniques could change the quality and/or quantity of the secondary metabolites responsible for the plant's therapeutic effects (Saeidirad et al., 2025; Chaji et al., 2024).

Common drying methods include air drying (in the shade, in an open location), drying in an oven at low temperatures, and more sophisticated methods such as freeze-drying (drying through freezing while the sample is in a vacuum) (Suresh et al., 2026; Roohinejad et al., 2025). The drying method often depends on the active constituents of the plant; for example, the loss of volatile compounds due to high drying temperatures, as well as the degradation of heat-labile compounds (Ming et al., 2025; Altay et al., 2024).

Preservation, on the other hand, is to maintain the chemical integrity and bioactivity of the extracts or dried plant material for the long term. This usually can be best accomplished through the use of an airtight container, protection from light, moisture, and extreme temperatures, to avoid or reduce oxidation and other degradation (Makhloufi, M., et al, 2025; Elhasnaoui, A et al., 2025; Makhloufi, D. A. 2021).

Due to the substantial amounts of polyphenols, flavonoids, and condensed tannins in *Matricaria pubescens*—metabolite groups that are susceptible to oxidative and thermal degradation—further examination of the appropriate drying and preservation conditions to retain more of these compounds will be necessary.

Although the phytochemistry of *Matricaria pubescens* has been extensively examined, a review of the literature reveals that no studies have been conducted on the drying kinetics of this plant. This lack of knowledge presents a significant research gap, since optimizing the drying process is necessary to standardize quality and to achieve adequate preservation of the bioactive compounds of this medicinal plant.

Thus, this study systematically evaluates the drying kinetics of *Matricaria pubescens* leaves and investigates the influence of air temperature and velocity on the drying kinetics.

Materials and Methods

Experimental Drying Procedure

The plant was harvested from the Bechar region of southwestern Algeria between February and April 2024. Only healthy plants were collected during sunny days. The harvested plants came from areas free of chemical fertilizers. To maintain sample quality, they were not crushed or stored in plastic bags. Before drying, the leaves were carefully separated from the stems. The initial moisture content of each harvest was measured immediately. A 100 g sample was used in the wind tunnel experiments. To determine moisture content before and after drying, the oven method was employed, which involved placing the sample at 105 °C for 24 hours and recording the mass loss to calculate the initial moisture content. The drying kinetics were studied in a laboratory wind tunnel under controlled conditions of temperature, air velocity, and humidity, using a Gunt-Hambuer-type device (CE130).

The wind tunnel is equipped with four corrosion-resistant trays positioned in the test section. The trays containing the product to be dried are exposed to an airflow. This airflow heats the solid and also removes any released moisture. The air speed can be adjusted using a fan, while an adjustable heating device heats the air.

The transparent door of the test chamber allows observation of the drying process. A digital balance is used to track changes in the solid's weight due to water evaporation during operation. Air temperature and relative humidity are measured and displayed using a temperature and humidity sensor, both before and after air passes through the product being dried. Another sensor measures the air velocity.

The measured parameters, such as weight change, humidity, temperature, and air velocity, can be directly transferred to a computer for further processing. The various components of the wind tunnel are illustrated in the figure below.

The principle of the experiment is to regulate the speed and temperature of the drying air for each trial. The system is left to stabilize for approximately one hour. Then, the product is spread in thin layers on the test trays. From this point on, the change in the product's mass is monitored. The time interval between two successive measurements is on the order of a few seconds (approximately 10 seconds). The drying experiments are continued until no further weight change is observed in three consecutive measurements.

To determine the dry mass, the product is placed in an oven set at 105°C until completely dehydrated (approximately 24 hours). At each stage of the drying process, the moisture content is calculated, and the drying curve is plotted over time. Three temperatures (30, 40, and 50°C) and three air velocities (0.5, 1, and 1.5 m/s) are selected, representing the most common conditions for drying medicinal and aromatic plants.

The objective of the kinetic study is to analyse the drying behaviour of the selected plant by plotting curves of water content as a function of time, drying rate as a function of time, and drying rate as a function of water content. The moisture content ratio, MR (or reduced water content), and the drying rate are calculated as follows:

$$MR = \frac{X_t - X_e}{X_0 - X_e} \quad (1)$$

where

X_t = moisture content at time t ,

X_e = equilibrium moisture content,

X_0 = initial moisture content.

$$\frac{dX}{dt} = \frac{X_{t+dt} - X_t}{dt} \quad (2)$$

where

X_t = moisture content at time t ,

X_{t+dt} moisture content at time $t+dt$,

dt time interval.

Effective moisture diffusivity (EMD)

Assuming that the diffusion coefficient is constant and that the shrinkage is negligible, the second Fick equation, which establishes a relationship between the diffusion coefficient and the concentration gradient in a given environment, can be used:

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \quad (3)$$

Where M is the local moisture content, r is the diffusion path, t is the time, and $Deff$ is the effective diffusivity coefficient. The analytical solution of Eq. (3) is

$$M_R = \frac{(M - M_e)}{(M_0 - M_e)} = \frac{8}{\pi^2} \sum \frac{1}{(2n + 1)^2} \exp - \frac{(2n + 1)^2 \pi^2 D_{eff} t}{4L^2} \quad (4)$$

Where M_0 is the initial moisture content, M_e is the equilibrium moisture content, and M is the moisture content at time t . M_R is the moisture ratio, and $n=1,2,3...$ is the number of terms taken into consideration. $Deff$ is the effective diffusivity (m^2/s), t is the time in seconds, and L is the half-thickness of the sample. With increasing drying time, all terms except the first become negligible. It is possible to calculate $Deff$ as follows (Crank, 1975):

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

The effective diffusivity ($Deff$) is determined from the slope of the normalized natural logarithm of the moisture ratio ($\ln(M_R)$) against time,

$$K = \frac{(\pi^2 D_{eff})}{(4L^2)} \quad (6)$$

The effect of temperature on the effective diffusivity ($Deff$) is determined according to the Arrhenius relationship:

$$D_{eff} = D_0 \exp \frac{E_a}{R(T + 273,15)} \quad (7)$$

where D_0 is the pre-exponential factor (m^2/s), E_a is the activation energy for moisture diffusion (kJ/mol), R is the universal gas constant (kJ/mol.K), and T is the absolute temperature ($^{\circ}C$).

Modelling of drying curves

Modelling drying curves involves identifying suitable mathematical models that describe the drying behaviour of the species. This approach relies on nonlinear regression, performed using the Curve Expert 1.6 software, which establishes a correlation expressing the evolution of reduced moisture content (RM) over time.

Seven mathematical models of thin-film drying (Page, Newton, Henderson and Pabis, Logarithmic, Two-term, Wang and Singh, Midilli and Kucuk.) (see Table 1) were used.

The best model was selected based on the analysis of statistical parameters, particularly the correlation coefficient R^2 , which is one of the main criteria for selecting the most appropriate model.

The goodness of fit was also assessed using various statistical parameters such as the reduced chi-square (χ^2) and root mean square error (RMSE) values. For a good fit, the coefficient of determination (R^2) should be high, while the values of χ^2 and RMSE should be low (Onwude S. K et al., 2020)

The statistical parameters are calculated using the following formulas:

$$R^2 = \frac{\sum_{i=0}^N (MR_i - MR_{prei}) \sum_{i=0}^N (MR_i - MR_{expi})}{\sqrt{\sum_{i=0}^N (MR_i - MR_{prei})^2 \sum_{i=0}^N (MR_i - MR_{expi})^2}} \quad (8)$$

$$\chi^2 = \frac{\sum_{i=0}^N (MR_{expi} - MR_{predi})^2}{N - n} \quad (8)$$

$$RMSE = \frac{1}{N} \sqrt{\sum_{i=0}^N (MR_{expi} - MR_{predi})^2} \quad (9)$$

Where

MR_{expi} is the i-th experimental reduced moisture content,

MR_{predi} is the i-th predicted reduced moisture content,

MR_i is the average observed reduced moisture content,

N is the number of observations,
n is the number of drying constants.

Table 1: Mathematical models used to describe the drying kinetics of *Matricaria pubescens* leaves.

Model Name	Model Equation	References
Newton	$MR = \exp(-Kt)$	Jayas et al., 1991
Page	$MR = \exp(-Kt^n)$	Page, 1949
Henderson and Pabis	$MR = a \exp(-Kt)$	Henderson and Pabis, 1961
Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh, 1978
Logarithmic	$MR = a \exp(-Kt) + c$	Chandra and Singh, 1995
Midilli and Kucuk	$MR = a \exp(-Kt^n) + bt$	Midilli and Kucuk, 2003
Two terms	$MR = a \exp(-Kt) + b \exp(-k_1 t)$	Henderson, 1974

Results and Discussion

Drying kinetics of the *M. pubescens* leaves.

The drying experiments were conducted at three drying air temperatures (30°C, 40°C, and 50°C), and for three air velocities (0.5 m/s, 1 m/s, and 1.5 m/s).

The initial moisture content for *Matricaria pubescens* leaves was 4% ($\pm 0.3\%$, dry basis). This moisture was reduced to a final moisture content ranging from 0.1 to 0.3% (dry basis). The ambient temperature and absolute humidity during the drying period varied from 24°C to 33°C and from 32% to 40%, respectively. The drying process was considered complete upon stabilization of the sample mass. Figure 1 shows the drying curve of *Matricaria pubescens* leaves. This curve shows the water content as a function of drying time under different air-drying conditions.

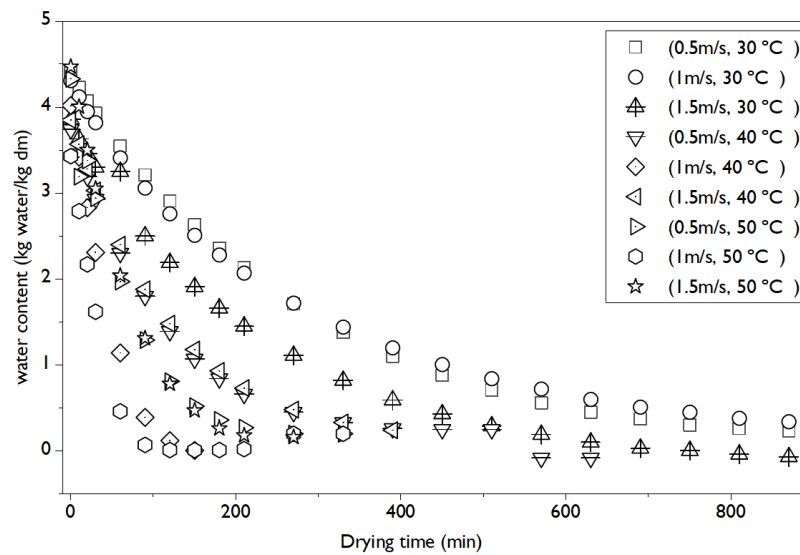


Figure. 1 drying curve of *Matricaria pubescens* leaves.

As shown in the curves, aerothermal parameters significantly influence the shape of the drying curves.

Figure 2 illustrates the total drying time of the species as a function of temperature, at a constant air velocity. It is clear that at low temperatures, the total drying time is much longer than at high temperatures, regardless of air velocity.

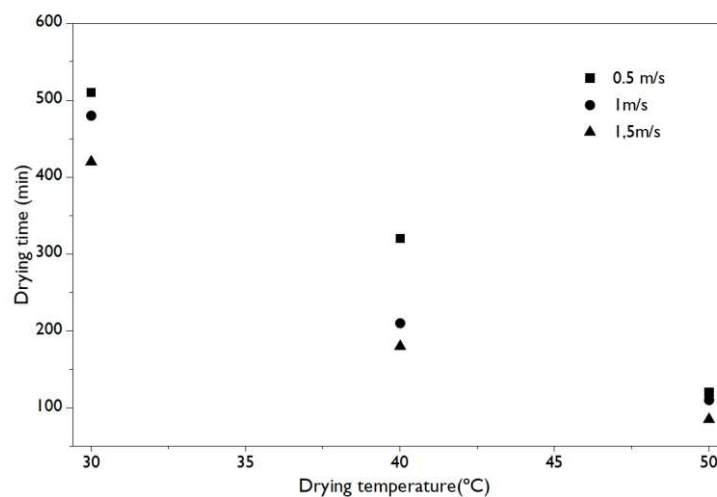


Figure 2 Drying time of *Matricaria p* as a function of air temperature at different air velocities.

Indeed, for a constant air velocity of 1 m/s, the drying time is reduced by approximately two-thirds when the temperature increases from 30°C to 50°C.

Furthermore, the effect of air velocity on drying time is more pronounced at low temperatures than at high temperatures. In other words, the impact of air temperature on drying time is more significant than that of air velocity.

Similar results have been reported for thin-layer drying of other *Matricaria* species, like chamomile flowers (Svetkov, I. T. et al., 1985)

The drying rate of the species was calculated, and its evolution over time is shown in Figure 3. As expected, drying occurs primarily during the phase where the rate decreases, due to the rapid removal of moisture. During this period, water migration occurs via a diffusion mechanism. The strong dependence of the drying rate on air temperature has been widely reported in the drying kinetics of various biological materials, such as onions (Demiray et al., 2016) and fruit pulp from the aromatic medicinal plant *Aegle marmelos* (Rayaguru & Routray, 2011).

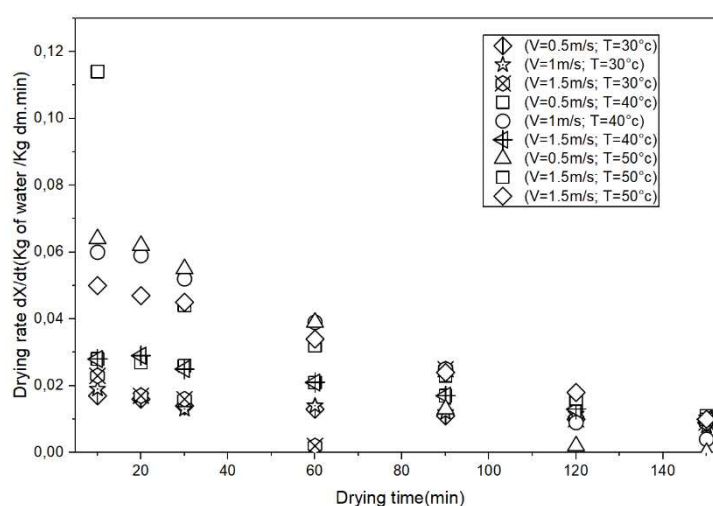


Figure 3. Evolution of the drying rate of *Matricaria.p* over time.

Figure 4 illustrates the drying curve of the plant studied under different air temperatures and constant air velocities of 0.5, 1, and 1.5 m/s. It is clear that the drying rate increases with rising drying air temperature, thus resulting in a significant reduction in drying time. Indeed, as the temperature difference between the drying air and the leaves of the species increases, the heat transfer coefficient also increases, which improves both the heat and mass transfer rates.

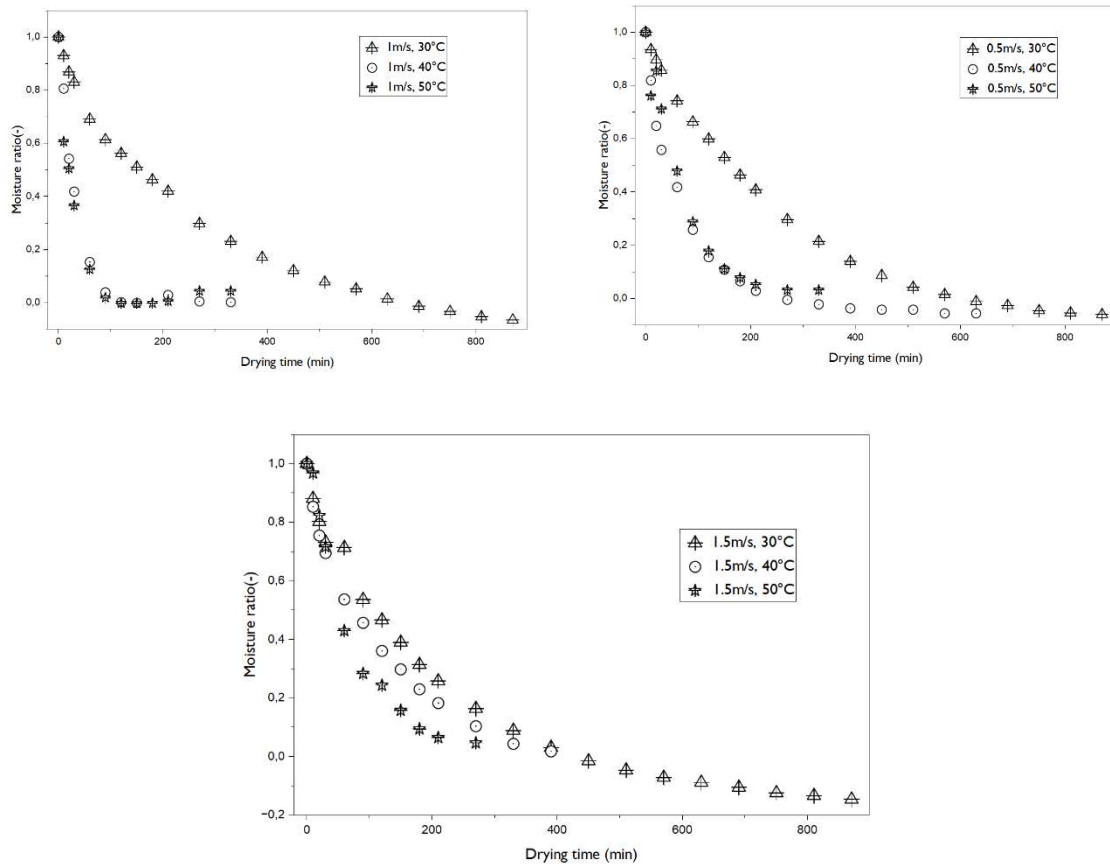


Figure .4 Drying curve of *Matricaria p* under different air temperatures and constant air velocities of 0.5, 1, and 1.5 m/s.

Figure 5 shows the variations in drying rates with respect to moisture content at different temperatures. The figure reveals a pronounced falling rate period. It is observed that as the water content decreases, the diffusion rate of moisture within the product and, consequently, the drying rate decrease. As also indicated in the figures, the drying rate increases with temperature until it reaches its maximum at $T = 50^{\circ}\text{C}$. similar trends have been consistently reported in the drying kinetics of various medicinal plants, such as mint leaves (Soysal & Öztekin, 2001) and lemon verbena (Doymaz, 2013), as well as in food products like pumpkin slices (Doymaz, 2007).

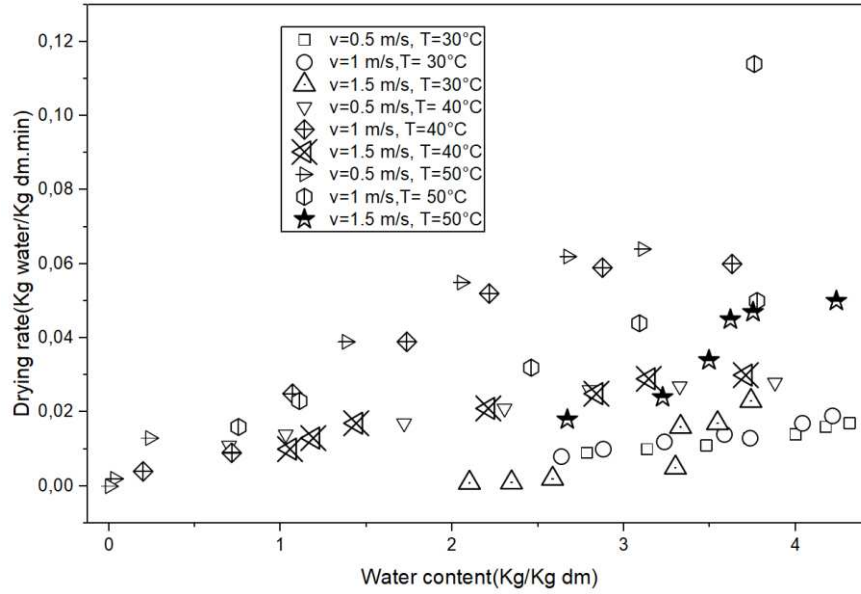


Figure 5. variations in drying rates with respect to moisture content at different temperatures.

The drying curves of *Matricaria pubescens* leaves at air velocities of 0.5, 1, and 1.5 m/s and air temperatures of 30°C, 40°C, and 50°C show that air velocity does not significantly affect the drying kinetics or the evolution of moisture content during the drying process. These results indicate that the limiting factor in drying is water transfer within the leaves, rather than the evaporation of water at the product surface.

According to Koukouch, A. et al. (2017), the effect of air velocity was statistically insignificant during the drying of basil leaves. The authors concluded that internal resistance was the dominant factor controlling the drying process. Its effect on drying is minimal when internal diffusion is the limiting factor in the drying process. The movement of air is particularly important during the initial drying stages when external mass transfer mechanisms dominate. Similar findings regarding the effect of air velocity on drying kinetics have been reported for leaves of *Allium roseum* (Ben Haj Said et al., 2015) and laurel leaves (Ghnimi et al., 2017).

Modelling of drying kinetics

The estimated coefficients for each model, along with their corresponding values of R^2 , χ^2 , and RMSE, are presented in Tables 2 to 4. All models satisfactorily describe the thin-layer drying kinetics of *Matricaria pubescens* leaves under all applied drying conditions. the coefficients of determination (R^2) ranged from 0.970 to 0.999, while the coefficients χ^2 and RMSE ranged from 0.119×10^{-3} to 4.16×10^{-3} and from 10.6×10^{-3} to 63.2×10^{-3} , respectively

By comparing these different statistical parameters, the Midilli and Kucuk model was selected as the most appropriate for predicting the drying characteristics of *Matricaria pubescens* leaves. The Midilli-Kucuk model was identified as the most suitable, which aligns with results reported

for lemon balm leaves (Akpınar, 2010) and mint leaves (Özcan et al., 2017). It was also observed that the rate constant (k) of the different models increases with increasing temperature. This increase in the drying constant as a function of temperature has also been demonstrated in the original work by Midilli et al. (2002) and supported by recent reviews (Onwude et al., 2020).

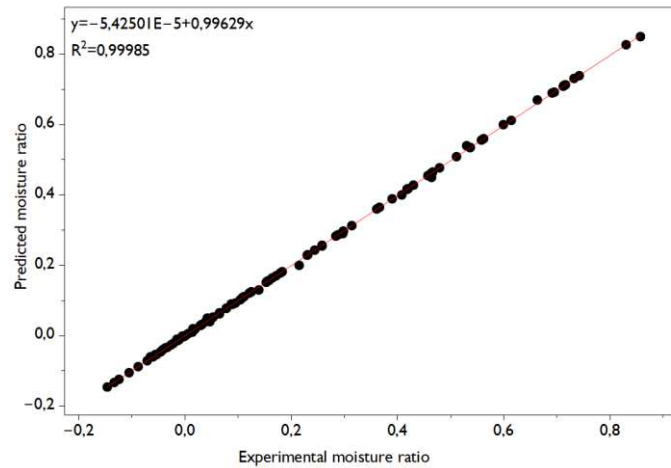


Figure 6. Predicted moisture ratio vs experimental moisture ratio for *Matricaria p* leaves

Figure 6 shows the agreement between the drying curves calculated using the Midilli and Kucuk model and the experimental drying curves for *Matricaria pubescens* leaves.

Table 2. Results of the modelling of the drying kinetics of *Matricaria p* at v=0.5 m/s

Model	Parameters	30°C	40°C	50°C
Page	R ²	0.9950	0.9960	0.9880
	RMSE ($\times 10^{-3}$)	8.5	6.2	25
	χ^2	0.028	0.025	0.062
	Coefficients	k=0.003, n=1	k=0.008, n=1	k=0.003, n=1
Newton	R ²	0.9940	0.9960	0.9780
	RMSE ($\times 10^{-3}$)	13	7.5	48
	χ^2	0.035	0.028	0.085
	Coefficients	k=0.005	k=0.007	k=0.012
Henderson et Pabis	R ²	0.9940	0.9960	0.9800
	RMSE ($\times 10^{-3}$)	13	6.8	42
	χ^2	0.035	0.026	0.078
	Coefficients	a=1, k=0.005	a=1, k=0.007	a=1, k=0.013
Logarithmic	R ²	0.9996	0.9975	0.9996
	RMSE ($\times 10^{-3}$)	0.45	4.2	0.42
	χ^2	0.006	0.022	0.008
	Coefficients	a=1, k=0.004, c=-0.08	a=1, k=0.006, c=-0.025	a=1.2, k=0.007, c=-0.32
Two Term	R ²	0.9940	0.9960	0.9800
	RMSE ($\times 10^{-3}$)	13	6.8	26
	χ^2	0.038	0.028	0.092
	Coefficients	a=1, k ₁ =0.005, b=0.025, k ₂ =0.005	a=-0.85, k ₁ =0.006, b=0.035, k ₂ =0.008	a=0.75, k ₁ =0.015, b=0.085, k ₂ =0.015
Wang et Singh	R ²	0.9930	0.9840	0.9992
	RMSE ($\times 10^{-3}$)	18	38	1.35
	χ^2	0.041	0.065	0.015
	Coefficients	a=-0.003, b=5 $\times 10^{-6}$	a=0.005, b=8 $\times 10^{-6}$	a=-0.008, b=2 $\times 10^{-5}$
Midilli et Kucuk	R ²	0.9998	0.9992	0.9996
	RMSE ($\times 10^{-3}$)	0.015	1.4	0.48
	χ^2	0.0042	0.014	0.011

Table 3. Results of the modelling of the drying kinetics of *Matricaria p* at v=1 m/s

Model	Parameters	30°C	40°C	50°C
Page	R ²	0.9970	0.9980	0.9900
	RMSE (×10 ⁻³)	7.2	4.5	20
	χ ²	0.024	0.021	0.054
	Coefficients	k=0.004, n=1	k=0.01, n=1	k=0.004, n=1
Newton	R ²	0.9960	0.9980	0.9810
	RMSE (×10 ⁻³)	11	4.8	41
	χ ²	0.03	0.021	0.071
	Coefficients	k=0.006	k=0.009	k=0.016
Henderson et Pabis	R ²	0.9960	0.9980	0.9830
	RMSE (×10 ⁻³)	11	4.2	36
	χ ²	0.03	0.02	0.07
	Coefficients	a=1, k=0.006	a=1, k=0.009	a=1, k=0.017
Logarithmique	R ²	0.9998	0.9980	0.9998
	RMSE (×10 ⁻³)	0.36	3.03	0.34
	χ ²	0.005	0.018	0.007
	Coefficients	a=1, k=0.005, c=-0.1	a=1, k=0.008, c=-0.03	a=1.3, k=0.009, c=-0.37
Two Term	R ²	0.9960	0.9980	0.9830
	RMSE (×10 ⁻³)	11	4.2	21
	χ ²	0.033	0.023	0.085
	Coefficients	a=1, k ₁ =0.006, b=0.03, k ₂ =0.006	a=-0.9, k ₁ =0.008, b=0.04, k ₂ =0.01	a=0.8, k ₁ =0.02, b=0.1, k ₂ =0.02
Wang et Singh	R ²	0.9950	0.9860	0.9995
	RMSE (×10 ⁻³)	15	32	1.09
	χ ²	0.036	0.057	0.012
	Coefficients	a=-0.004, b=6×10 ⁻⁶	a=0.006, b=10 ⁻⁵	a=-0.01, b=3×10 ⁻⁵
Midilli et Kucuk	R ²	0.9999	0.9995	0.9998
	RMSE (×10 ⁻³)	0.011	1.1	0.35
	χ ²	0.0033	0.011	0.008

Table 2. Results of the modelling of the drying kinetics of *Matricaria p* at v=1.5 m/s

Model	Parameters	30°C	40°C	50°C
Page	R ²	0.9980	0.9990	0.9930
	RMSE (×10 ⁻³)	5.8	3.2	15
	χ ²	0.019	0.016	0.042
	Coefficients	k=0.005, n=1	k=0.012, n=1	k=0.005, n=1
Newton	R ²	0.9970	0.9990	0.9850
	RMSE (×10 ⁻³)	8.5	3.5	32
	χ ²	0.025	0.015	0.058
	Coefficients	k=0.007	k=0.011	k=0.020
Henderson et Pabis	R ²	0.9970	0.9990	0.9870
	RMSE (×10 ⁻³)	8.5	3.1	28
	χ ²	0.025	0.014	0.052
	Coefficients	a=1, k=0.007	a=1, k=0.011	a=1, k=0.021
Logarithmique	R ²	0.9999	0.9990	0.9999
	RMSE (×10 ⁻³)	0.25	2.1	0.22
	χ ²	0.003	0.012	0.004
	Coefficients	a=1, k=0.006, c=-0.12	a=1, k=0.010, c=-0.035	a=1.4, k=0.011, c=-0.42
Two Term	R ²	0.9970	0.9990	0.9870
	RMSE (×10 ⁻³)	8.5	3.1	18
	χ ²	0.027	0.016	0.068
	Coefficients	a=1, k ₁ =0.007, b=0.035, k ₂ =0.007	a=-0.95, k ₁ =0.010, b=0.045, k ₂ =0.012	a=0.85, k ₁ =0.025, b=0.115, k ₂ =0.025
Wang et Singh	R ²	0.9960	0.9890	0.9997
	RMSE (×10 ⁻³)	12	25	0.85
	χ ²	0.030	0.045	0.008
	Coefficients	a=-0.005, b=7×10 ⁻⁶	a=0.007, b=1.2×10 ⁻⁵	a=-0.012, b=4×10 ⁻⁵
Midilli et Kucuk	R ²	1.0000	0.9998	0.9999
	RMSE (×10 ⁻³)	0.008	0.8	0.25
	χ ²	0.0025	0.008	0.005

The effect of temperature and air velocity on effective water diffusivity.

The slope method was used to calculate the effective water diffusivities (Deff) of the plant. The variation of experimental ln(MR) with drying time for *Matricaria pubescens* leaves, under different temperature and air velocity conditions, is shown in Figure 7. A linear relationship was found between ln(MR) and drying time with a coefficient of determination greater than

0.95. Equation (5) and the slopes derived from the linear regressions allowed the calculation of the effective water diffusivity for each test.

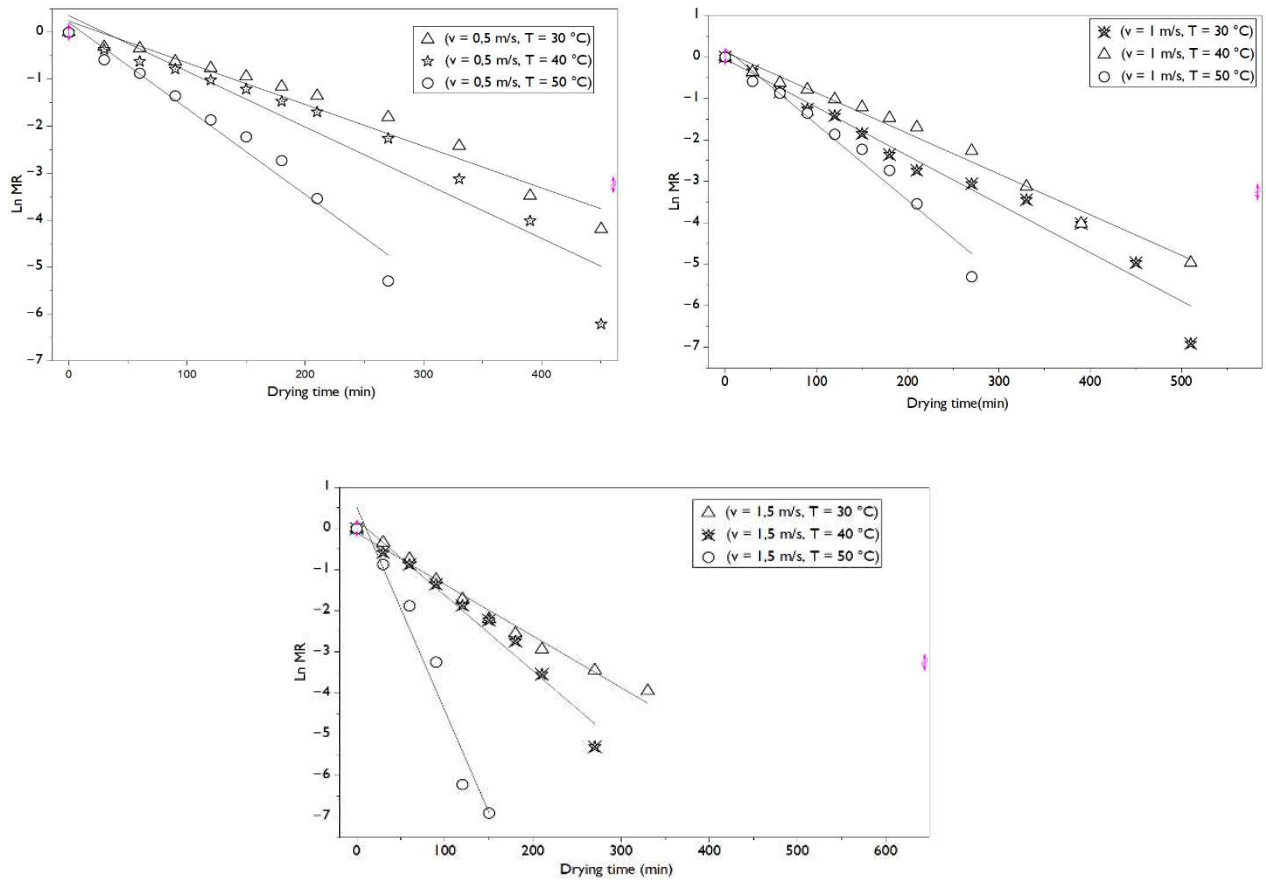


Figure 7 variation of experimental $\ln(MR)$ with drying time for *Matricaria pubescens* leaves, under different temperature and air velocity conditions

The moisture diffusivity values of *Matricaria pubescens* leaves are summarized in Table 5; the calculated water diffusivities range from 1.58×10^{-11} to 1.58×10^{-11} m²/s. The minimum water diffusivity value was 1.58×10^{-11} – 1.58×10^{-11} m²/s at an air velocity of 0.5 m/s and temperature of 30°C, while the maximum water diffusivity was 23.17×10^{-11} – 23.17×10^{-11} m²/s at an air velocity of 0.5 m/s and temperature of 50°C. In general, the value of effective diffusivity (De_{eff}) varies between 10^{-11} and 10^{-9} m²/s for foods (Rao et al., 2014). It was also observed that an increase in air velocity decreases the value of (De_{eff}), especially at temperatures of 40°C and 50°C. This is because at low air velocity, the air has better contact with the sample surface, which leads to significant moisture absorption. Consequently, the moisture gradient between the sample and the surrounding air increases, resulting in an increase in water diffusivity. However, at high air velocities, the air passing through the sample becomes turbulent, so the moisture gradient decreases and water diffusivity decreases accordingly.

Table.5 The effective diffusivity values of *Matricaria pubescens* leaves

Drying conditions		Effective Diffusivity ($\times 10^{-11}$ m ² /s)	R ²
V (m/s)	T(°C)		
0.5	30	2.29	0.995
	40	5.63	0.933
	50	30.60	0.925
1.0	30	2.36	0.990
	40	29.00	0.970
	50	30.23	0.988
1.5	30	3.16	0.928
	40	5.34	0.934
	50	10.70	0.977

The effective moisture diffusivities ($Deff$) values for *Matricaria pubescens* leaves ranged from 2.29×10^{-11} to 30.60×10^{-11} m²/s. The minimum value of $Deff$ was observed at 0.5 m/s and 30°C, while the maximum value was recorded at 50°C with a low-to-moderate air velocity of 0.5 m/s. In general, the value of the effective diffusivity ($Deff$) for food products ranges from 10^{-11} to 10^{-9} m²/s (Rao et al., 2014). It was also observed that an increase in air velocity decreases the value of $Deff$, particularly at temperatures of 40°C and 50°C. This is because, at a low air velocity, the air has better contact with the sample surface, leading to significant moisture absorption. Consequently, the moisture gradient between the sample and the surrounding air increases, which results in an increase in water diffusivity. However, at high air velocities, the air passing over the sample becomes turbulent, so the moisture gradient decreases and the water diffusivity is consequently reduced.

Several authors have reported similar observations on the effects of temperature and air velocity on water diffusivity, including Mirzaee et al. (2009) for the drying of apricots and Sacilik and Elicin (2006) for the drying of apple slices.

Estimation of activation energy

Figure 8 shows the curve representing $\ln(D_{eff})$ with drying temperature for *Matricaria pubescens* leaves. The activation energy for water diffusion was obtained using equation 7 and the calculated slopes. The activation energy (E_a) values are summarized in Table 6.

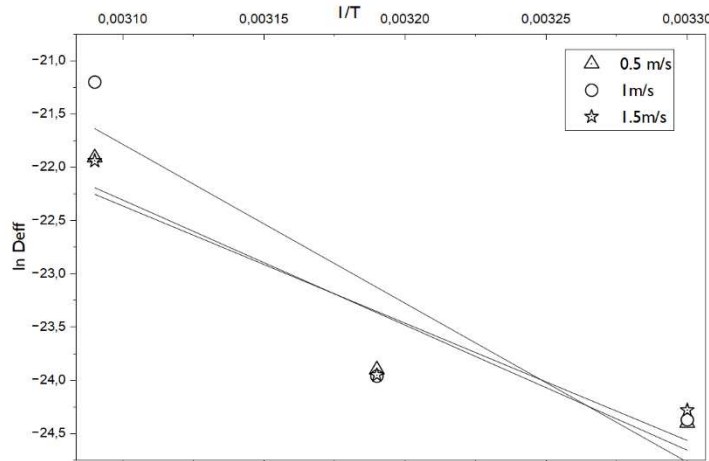


Figure 8 variation of $\ln(D_{eff})$ with drying temperature for *Matricaria pubescens* leaves.

Table 6. The activation energy (E_a) values of *Matricaria p*

Air Velocity (m/s)	Activation Energy, E_a (kJ/mol)	R^2
0.5	64.98	0.998
1.0	80.18	0.967
1.5	62.57	0.998

The activation energy of *Matricaria pubescens* was estimated to be approximately 64.98 kJ/mol, 80.18 kJ/mol, and 62.57 kJ/mol for drying air velocities of 0.5, 1, and 1.5 m/s, respectively.

A relatively high activation energy of 80.18 kJ/mol at low air velocity indicates that the drying kinetics are strongly temperature-dependent. This confirms that the limiting mechanism is internal moisture diffusion. Consequently, increasing the temperature will significantly accelerate the process.

A study by Onwude, D. I., et al. (2016) consistently notes that for porous biological materials, when internal diffusion is dominant, the reported activation energies are generally high (often in the range of 30 to 110 kJ/mol), confirming a strong temperature dependence.

The characteristic drying curve

The characteristic drying curve approach is a simple method used to interpolate a curve with a decreasing rate under relatively narrow operating conditions. It was first proposed by Van Meelen 1958, who observed that the curve representing the normalized drying rate as a function

of normalized moisture content was practically independent of drying conditions (Kemp et al., 2001; Sablani et al., 2006; Chen and Mujumdar, 2008). This empirical approach has been successfully used to correlate the drying kinetics of small-sized products (Keey, 1992).

The fitting of the characteristic drying curves allowed the determination of the characteristic equation of the drying rate in the form of a second-degree polynomial. The statistical criteria used to select the equations that best describe the characteristic drying curves are the correlation coefficient R^2 . Similar finding was reported by Yaldiz, O et al, 2001.

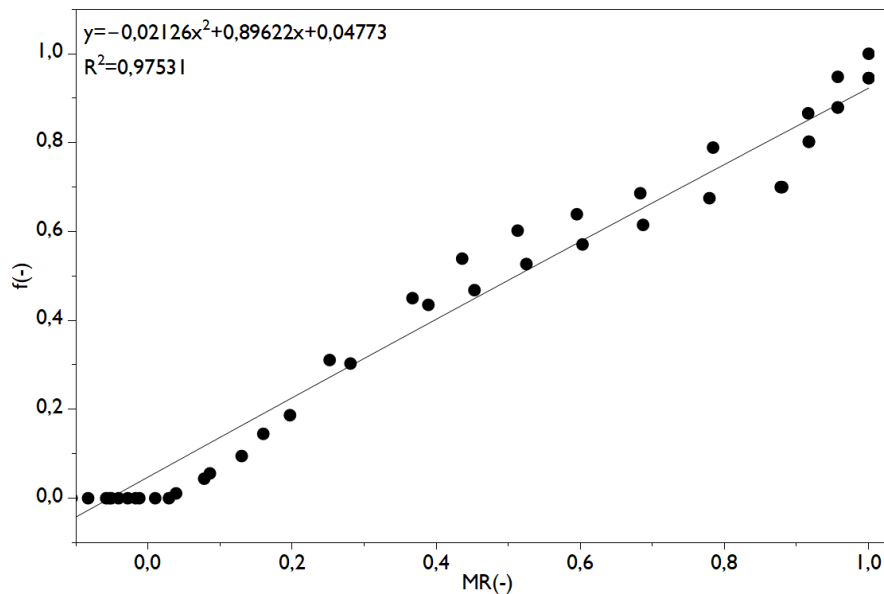


Figure 9. Characteristic drying curve of *Matricaria pubescens* leaves

Conclusion

The study of the drying kinetics of *Matricaria pubescens* allowed us to analyse its drying behaviour by plotting the curves of moisture content versus time, drying rate versus time, and drying rate versus moisture content. These curves showed that the drying rate increases with increasing temperature of the drying air and therefore reduces the drying time. It was also concluded that air velocity has no significant effect on the drying kinetics and did not affect the evolution of moisture content during the drying process, which implies that the limiting factor of drying is the transfer of water inside the leaves and not the evaporation of water at the product surface.

The determination of the appropriate models that describe the drying behaviour of the species involved establishing, using the non-linear regression method, a correlation that gives the evolution of the moisture ratio (MR) as a function of time. Seven mathematical models of thin-layer drying (Page, Newton, Henderson and Pabis, Logarithmic, Two-term, Wang and Singh, Midilli and Kucuk.) were used. By comparing the different statistical parameters (R^2 , χ^2 , and

RMSE), the Midilli and Kucuk model was selected as the one that best predicts the drying characteristics of *Matricaria pubescens*.

The slope method was used to calculate the effective moisture diffusivities ($Deff$), and the values ranged from 2.29×10^{-11} to $30.60 \times 10^{-11} \text{ m}^2/\text{s}$.

The characteristic drying curve (CDC) approach was used. This approach can be employed to represent the drying kinetics of a product without needing to know its physical characteristics. The fitting of the characteristic drying curves for the plant allowed for the determination of the characteristic drying rate equation in the form of a second-degree polynomial.

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