

# NOVEL MATHEMATICAL MODEL WITH INTEGRATIVE OPTIMIZATION FOR MICROWAVE DRYING OF OLIVE LEAVES (*OLEA EUROPAEA*) TO ENHANCE BIOACTIVE COMPOUNDS PRESERVATION, ANTIOXIDANT ACTIVITY, AND ENERGY EFFICIENCY

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**ABSTRACT.** This study optimized the microwave drying of olive leaves by integrating mathematical modeling and proposing a novel drying model, along with a comprehensive analysis of energy efficiency and bioactive compound preservation. Experiments were conducted at microwave power levels ranging from 100 to 1000 W, assessing drying kinetics, energy efficiency, and retention of bioactive compounds. The optimal power of 700 W achieved a drying time of 21 minutes while preserving key bioactive compounds, with TPC, TFC, and antioxidant activity reaching 108.79 mg GAE/g DM, 12.12 mg RE/g DM, and 23.25 mg GAE/g DM, respectively. Several mathematical models from the literature were evaluated, and the Logarithmic, Modified Henderson–Pabis II, and Hii et al. models showed excellent agreement with the experimental data ( $R^2 > 0.99$ ). The proposed new model also demonstrated strong predictive accuracy, with high  $R^2$  values and low root mean square error and reduced chi-square ( $\chi^2$ ). The lowest specific energy consumption was  $0.236 \times 10^5$  MJ/kg  $H_2O$ , accompanied by the highest energy efficiency. These results demonstrate that intermediate

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microwave power provides an optimal balance between energy efficiency, processing time, and bioactive compound preservation, highlighting both practical and economic advantages for olive leaf drying.

**Keywords:** *Microwave drying, olive leaves, bioactive compounds, antioxidant activity, mathematical modeling, energy efficiency*

## INTRODUCTION

*Olea europaea* L. is a species within the Oleaceae family, it is native to the Mediterranean region and is of significant economic and social importance. Historically, olive leaves have been used in traditional medicine to treat various conditions, including fevers, malaria, rheumatism, hypertension, diabetes, and cancer. Their extracts have garnered attention as natural additives in cosmetics, functional foods, and pharmaceuticals [1]. Fresh olive leaves generally need to be dried and ground before extraction to preserve bioactive compounds and ensure optimal extraction efficiency. This process prevents microbial and enzymatic degradation that could compromise the quality of the final product [2].

Several studies have investigated various methods for drying olive leaves, including air, convection, and solar drying [3–5]. However, these techniques exhibit notable limitations [6]. A high temperature during air drying can cause significant losses in polyphenols [7], particularly due to the degradation of compounds like oleuropein. Sun drying requires significant space and time, with minimal control over the process. Additionally, the leaves are exposed to dust and environmental contamination [8].

Modern drying methods, such as microwave drying, offer promising alternatives. Microwave drying generates volumetric heating, significantly shortening treatment time [9,10]. This minimizes the risk of alterations caused by prolonged heating in conventional processes. The combination of optimal heating power and shorter processing times helps preserve thermolabile compounds, maintain antioxidant activity, and reduce changes in the organoleptic and sensory properties of the products, particularly in terms of texture, color, taste, and aroma [11,12].

Despite its advantages, research on microwave drying remains limited, particularly regarding mathematical modeling and its impact on antioxidant preservation. Current models tend to overlook an integrated approach that could combine both mathematical modeling and the analysis of biological properties, which is crucial for improving outcomes [13].

This study presents an integrated approach to optimize microwave drying of olive leaves by combining mathematical modeling with an analysis of parameters influencing antioxidant retention. Thin-layer kinetic modeling is applied, testing 52 models to identify the best fit. A new drying kinetics model is proposed to improve the prediction of moisture removal dynamics and energy efficiency under varying microwave power levels. The study employs a multimodal approach, integrating advanced experimental techniques and detailed modeling of heat and mass transfer. Key parameters analyzed include drying time, microwave power, moisture content (MC), drying rates (DR), and effective moisture diffusivity ( $D_{eff}$ ). Energy analysis includes activation energy ( $E_a$ ), specific energy consumption (SECe), and energy efficiency (EE). Furthermore, the study evaluates both qualitative and quantitative properties of dried olive leaves, such as total phenolic content (TPC), total flavonoid content (TFC), and Radical scavenging activity (RSA), using principal component analysis (PCA) to explore relationships between drying conditions and product quality.

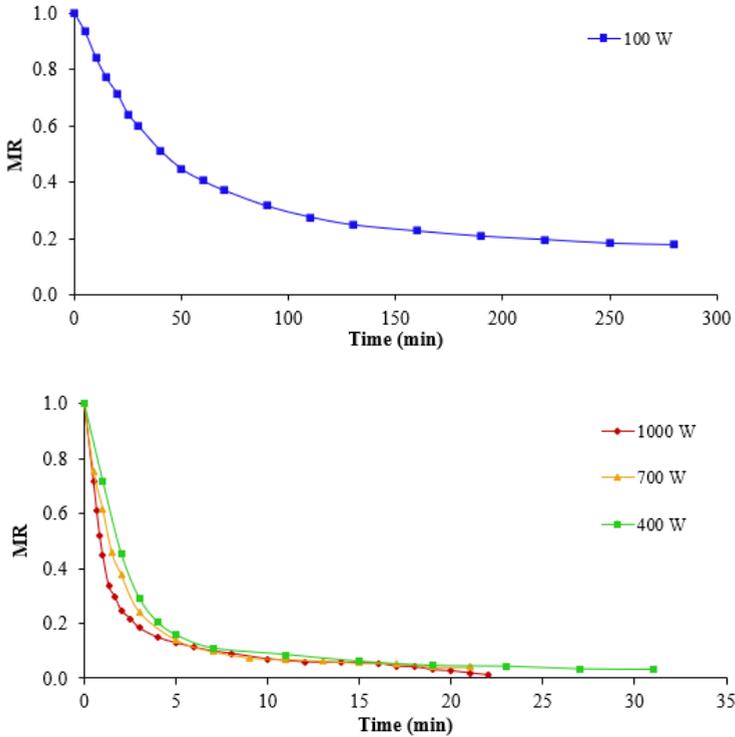
## RESULTS AND DISCUSSION

### Drying kinetics

In this study, the effect of varying microwave power levels on the drying of olive leaves was assessed, focusing on the relationship between relative moisture content and drying time. The drying curves obtained for each microwave power level are presented in Figure 1. These curves illustrate the evolution of MR in olive leaves over time (minutes) under different power settings: 100, 400, 700, and 1000 W. The variation in the time required to reach a constant weight of  $7.55 \pm 0.46$  g is depicted. The results reveal a clear inverse correlation between microwave power and drying time. At 100 W, the drying time is 280 minutes. When the power is increased to 400 W, the drying time decreases to 31 minutes. Further power increases reduce the drying time to 21 minutes at 700 W and 19 minutes at 1000 W. An increase in microwave power leads to a significant reduction in the drying time of olive leaves, particularly between 100 W and 400 W. However, beyond 400 W, the effect on drying time becomes less pronounced, suggesting that an optimal power threshold exists around 700 and 1000 W.

These findings demonstrate that higher microwave power levels accelerate the drying process by enabling more efficient energy absorption by water molecules. In agreement with [14], our results show that increasing

power enhances the rate of moisture evaporation, thereby shortening drying times. However, while higher power levels lead to reduced drying durations, it is essential to monitor the potential effects on product quality [15].



**Figure 1.** Evolution of the experimental moisture content with drying time for olive leaves at different microwave power levels

### Mathematical modeling of drying kinetics

The drying kinetics of olive leaves were analyzed using 52 mathematical models to describe the MR over time under various microwave powers. The results, including statistical analyses and key metrics such as drying constants, model coefficients,  $R^2$ ,  $\chi^2$ , and RMSE for the best-performing models, are summarized in Appendix A.

The analysis showed that the Logarithmic, Modified Henderson and Pabis II, and the Modified Hii et al. models emerged as the best-fit models and the most effective based on their high  $R^2$  values and the low  $\chi^2$  and

RMSE values. For these optimal models,  $R^2$  values ranged from 0.999054 to 0.999937,  $\chi^2$  values ranged from 0.000015 to 0.002829, and RMSE values ranged from 0.002905 to 0.039889.

These results demonstrate the exceptional performance of the selected models in fitting the experimental data. The three models effectively predict the drying kinetics of olive leaves across various microwave power settings, providing a high degree of precision in simulating the drying dynamics. This accuracy suggests that these models are valuable tools for modeling and optimizing the drying process of olive leaves.

Compared to previous studies, our findings align with those reported by [16,17]. These studies validated the suitability of various models for defining drying curves of medicinal plants and crops dried in thin layers. Including the modified Henderson and Pabis models for *Piper umbellatum* L. leaves [18] and *S. terebinthifolius* leaves [19]. The Hii model has been validated as the best model for coriander leaves [20] and cocoa beans [21]. Additionally, the logarithmic model was applied to *Moringa oleifera* leaves [22], scent leaves, and lemon basil leaves [3].

### **Validation of the proposed model**

In this study, a new double-exponential drying kinetics model was used. The constants  $a$ ,  $b$ ,  $c$ ,  $K_1$ , and  $K_2$  showed a strong correlation with the moisture ratio. The numerical values are summarized in Appendix A.

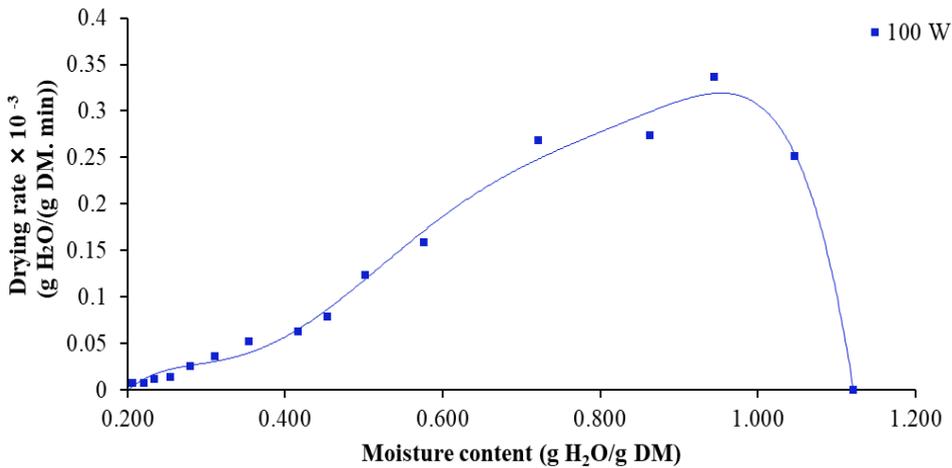
Residual analysis was performed to validate the proposed model. The results indicate an excellent correlation between the experimental and predicted data, with an  $R^2$  value of 0.9992. Considering the overall fit, the residuals are very close to zero and randomly distributed, confirming the model's reliability. The RMSE values ranged from 0.00573 to 0.00985, while  $\chi^2$  values varied between  $4.16 \times 10^{-5}$  and 0.0002927, further demonstrating the model's high accuracy in fitting the experimental data.

### **Drying rates VS. moisture content**

The drying rates of olive leaves as a function of moisture content are shown in Figure 2. The drying curves exhibit a sigmoidal shape, reflecting significant variations in the drying rate due to both moisture content and microwave power. Initially, the drying rate increases rapidly as microwave heating removes moisture, followed by a slower decline as the moisture content decreases and drying becomes less efficient.

The drying process can be divided into two distinct phases. During the initial heating phase, the drying rate increases significantly as the microwave power increases, particularly between 100 W and 400 W. At

100 W, the drying rate is  $0.251 \times 10^{-3}$  g water/g DM, while at 400 W, it increases to  $5.238 \times 10^{-3}$  g water/g DM, indicating a significant acceleration of moisture removal in the initial phase. At higher power levels (700 and 1000 W), the drying rates are similar with  $9.143 \times 10^{-3}$  and  $10.551 \times 10^{-3}$  g water/g DM, respectively. However, the increase in drying speed stabilizes beyond 400 W, indicating that the efficiency reaches a plateau at higher power levels rather than showing further significant improvements. Following this, in the decelerating phase, the drying rate decreases gradually. Notably, no constant-rate drying period is observed; all drying occurs during the falling-rate phase.



**Figure 2.** Variation of drying rate with moisture content of olive leaves dried at different microwave power levels

The average DR values recorded are  $0.1097 \times 10^{-3}$ ,  $1.274 \times 10^{-3}$ ,  $1.7296 \times 10^{-3}$ , and  $2.1275 \times 10^{-3}$  g water/ g DM. Sec for microwave powers of 100, 200, 400, and 1000 W, respectively. These results indicate that 700 W and 1000 W are the optimal power levels for rapid and efficient drying. The drying speed increases significantly between 100 W and 400 W, and then stabilizes at higher power levels, such as 700 W and 1000 W.

This behavior aligns with the principles of microwave drying, where higher microwave power enhances volumetric heating efficiency, accelerating heat and moisture transfer [23]. However, it is essential to monitor the temperature to prevent local overheating, which could potentially affect the bioactive properties of the leaves [24].

These findings are consistent with previous studies [25,26], affirming that microwave drying exhibits a characteristic model with an initial rapid drying phase followed by a period of decreasing rates, significantly influenced by microwave power. These observations highlight the importance of controlling microwave power to optimize the drying process while maintaining the quality of the final product [6].

### Effective moisture diffusivity

Understanding the mass transfer mechanisms in materials subjected to microwave drying fundamentally relies on effective diffusivity. The values of  $D_{\text{eff}}$  were determined under different microwave power levels (100 W, 400 W, 700 W, and 1000 W) and are presented in Table 1.

**Table 1:** Impact of microwave power on diffusivity during olive leaf drying

Power (W)	$D_{\text{eff}} \cdot 10^{-10} \pm \text{SD}$
100	$0.78 \pm 0.16^c$
400	$20.01 \pm 2.83^b$
700	$22.1 \pm 0.48^b$
1000	$30.78 \pm 0.39^a$

*Distinct letters within each column indicate statistically significant differences according to the ANOVA followed by Tukey's post-hoc test ( $p < 0.05$ ), with the order reflecting the magnitude of the results ( $a > b > c$ )*

The  $D_{\text{eff}}$  values obtained during microwave drying ranged from  $0.78 \times 10^{-10}$  to  $30.78 \times 10^{-10} \text{ m}^2/\text{s}$ , depending on the applied power. This interval is consistent with biologically active dried products [27].

The  $D_{\text{eff}}$  values increased significantly with increasing microwave power, ranging from  $0.78 \times 10^{-10} \text{ m}^2/\text{s}$  at 100 W to  $30.78 \times 10^{-10} \text{ m}^2/\text{s}$  at 1000 W. Statistical analysis indicated significant differences among the different power levels. Specifically, the  $D_{\text{eff}}$  at 100 W was significantly lower than those observed at higher power levels (400 W, 700 W, and 1000 W), which showed substantial increases in diffusivity.

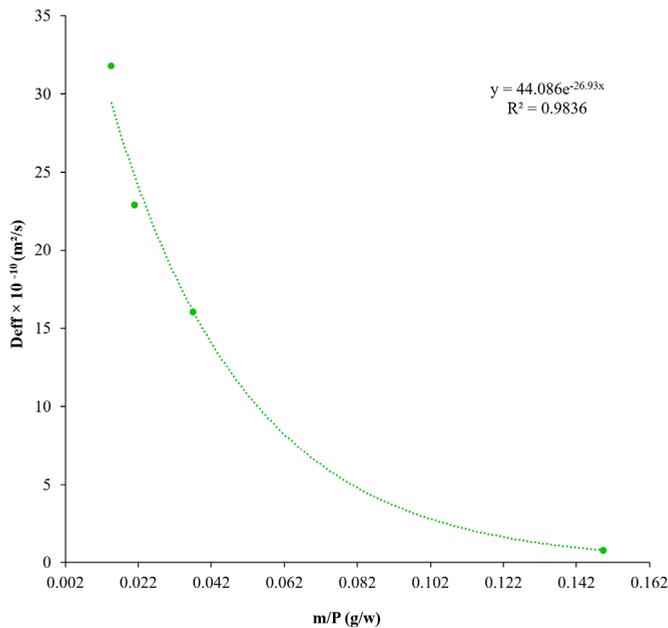
These findings are consistent with previous studies on microwave drying, where higher power levels increased moisture diffusivity due to enhanced energy transfer and water vaporization rates [28]. The rapid volumetric heating at higher powers promoted moisture migration, leading to greater  $D_{\text{eff}}$  values. The notable rise in  $D_{\text{eff}}$  at 1000 W indicates a stronger thermal gradient and higher vapor pressure within the olive leaf matrix,

facilitating more efficient moisture removal. This increase in  $D_{\text{eff}}$  can be explained by two key factors: reduced water viscosity and higher kinetic energy of water molecules at elevated power levels [29]. Microwave heating directly energizes water molecules, causing rapid temperature increases. However, careful control is necessary to prevent thermal imbalances, which could affect drying uniformity and product quality [28]. These results underscore the importance of optimizing microwave power for efficient drying.

## Total energy balance

### Activation energy

Figure 3 shows the relationship between effective moisture diffusivity and the sample ratio ( $m/P$ ). This trend allows for the evaluation of different samples based on their moisture diffusivity throughout the drying process. The obtained values for the pre-exponential factors  $D_0$  and  $E_a$  are  $4.33 \times 10^{-9} \text{ m}^2/\text{s}$  and  $26.94 \text{ W/g}$ , respectively.



**Figure 3.** Arrhenius plot for calculating the drying activation energy of olive leaves

These results indicate a moderate activation energy, reflecting relatively efficient heat transfer within the material. The high diffusivity value highlights

the effectiveness of the microwave drying process, facilitating rapid moisture removal. This efficiency is crucial for achieving uniform drying and minimizing drying time, due to the process's homogeneity [30,31].

Similarly, previous studies in the literature revealed that the *Ea* value aligns with those reported for thermal diffusion processes in similar matrices, typically between 20 and 30 W/g. This consistency with previous studies supports the validity of the experimental method and conditions used [30].

### ***Specific energy consumption and electrical energy***

The results for specific energy consumption and energy efficiency at each power level for drying olive leaves are presented in Table 2. SEC values show statistically significant variation across power levels. The lowest SEC is observed at 700 W, with a value of  $0.236 \times 10^5$  MJ/kg H<sub>2</sub>O, suggesting that a moderate increase in power optimizes energy efficiency.

**Table 2:** Energy efficiency and specific energy consumption of olive leaf drying at different power levels

<b>Power (W)</b>	<b>EE <math>\pm</math> SD (<math>\times 10^{-2}</math> %)</b>	<b>SEC <math>\pm</math> SD (<math>\times 10^5</math> MJ/kg H<sub>2</sub>O)</b>
100	133.506 $\pm$ 5.52 <sup>d</sup>	1.694 $\pm$ 0.0630 <sup>a</sup>
400	798.896 $\pm$ 7.37 <sup>b</sup>	0.283 $\pm$ 0.0352 <sup>c</sup>
700	963.824 $\pm$ 3.79 <sup>a</sup>	0.236 $\pm$ 0.0144 <sup>c</sup>
1000	219.837 $\pm$ 8.66 <sup>c</sup>	1.029 $\pm$ 0.0035 <sup>b</sup>

*Values are expressed as mean  $\pm$  standard deviation. Different letters within the same row indicate significant differences between treatments (ANOVA followed by Tukey's test  $p < 0.05$ .  $a > b > c$ )*

In contrast, higher SEC values at both lower (100 W) and higher (1000 W) power levels indicate inefficiencies, likely due to insufficient energy input at low power and excess thermal losses at high power. EE values vary significantly across power levels, with the highest efficiency observed at 700W, achieving  $963.82 \times 10^{-2}$  %. This suggests that intermediate power levels optimize energy use, while the lowest efficiency is seen at 100W, indicating a notable decrease in energy effectiveness at low power settings.

The results indicate that an intermediate power level of 700W balances energy input and process efficiency, minimizing SEC while maximizing EE. This inverse relationship between SEC and EE is consistent with previous studies showing that moderate power levels optimize energy use by balancing demand with evaporation rates [32–34].

## **Biological effect**

### ***Total phenolic content***

Figure 4 illustrates the total phenolic content of olive leaves dried at various microwave powers. As the microwave power increased from 100 W to 700 W, TPC was significantly affected by the microwave power ( $p < 0.05$ ), reaching a peak at 700 W with a value of 108.79 mg AGE/g DM.

However, a non-significant decrease was observed when the power increased from 700 W to 1000 W. These results might be due to the sensitivity of phenolic compounds to low microwave power (100 W), which requires a longer drying duration and might lead to increased degradation of these compounds. A moderate to high microwave power (700 and 1000 W) seems optimal for maximizing TPC. A similar trend has been observed in microwave drying, where an increase at higher power levels followed an initial decrease in total phenolic content [35], although beyond 500W, the TPC began to decline. Additionally, microwave drying of coriander leaves has demonstrated an enhancement in total phenolic content at higher power levels. Higher microwave power levels increase temperature and vapor pressure within plant tissues. This elevation may cause cell walls to rupture, facilitating the release of phenolic compounds, including those bound to the cell walls [13].

### ***Total flavonoid content***

Flavonoids are a diverse group of naturally occurring plant compounds known for their antioxidant properties. The effect of microwave drying on the flavonoid content of olive leaves was evaluated, with results shown in Figure 4. The data indicates that the average flavonoid concentrations ranged from 11.13 to 12.21 mg RE/g DM, depending on the microwave power levels applied. However, no statistically significant differences were observed between these values.

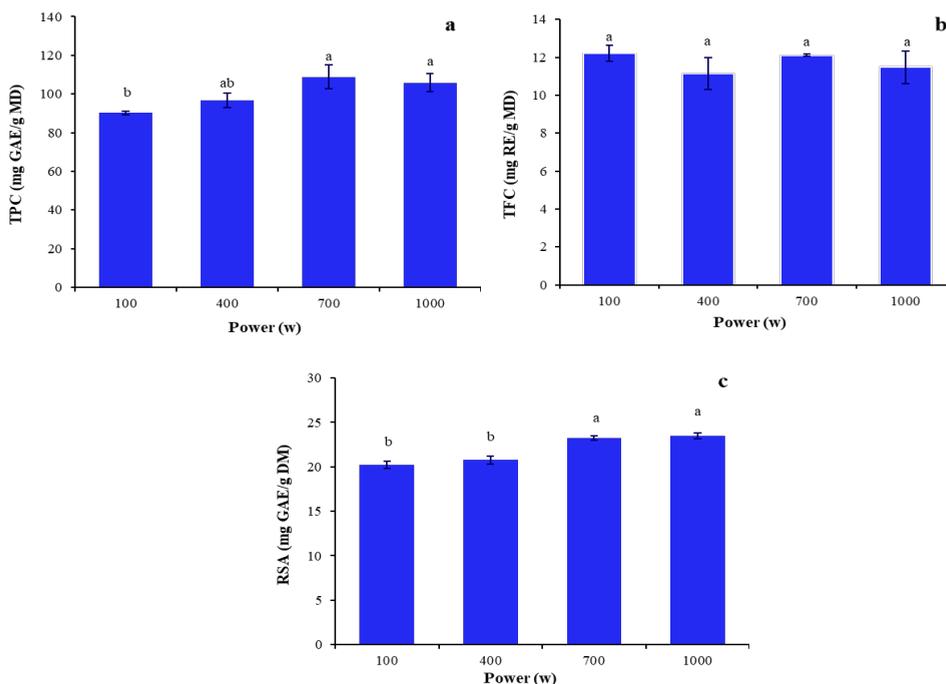
These findings suggest that variations in microwave power do not significantly impact the final flavonoid concentration in olive leaves. This is consistent with other studies on food products [18,36,37], which have also shown that changes in drying conditions, including microwave drying, do not substantially affect flavonoid content.

### ***Radical scavenging activity***

The antioxidant capacity of olive leaves dried under varying microwave power levels, assessed through the ABTS assay, is illustrated in Figure 4. The results showed that higher microwave power increased antioxidant activity,

with values of 23.25 and 23.49 mg GAE/g DM with no significant difference at 700 W and 1000 W, respectively. In contrast, at 100 W, antioxidant activity was lower, with values of 20.24 mg GAE/g DM.

The results show that higher microwave power levels enhance the preservation and activation of antioxidant compounds in olive leaves. At 700 W and 1000 W, antioxidant activity remained consistent, suggesting these power levels provide optimal conditions for maximizing antioxidant benefits.



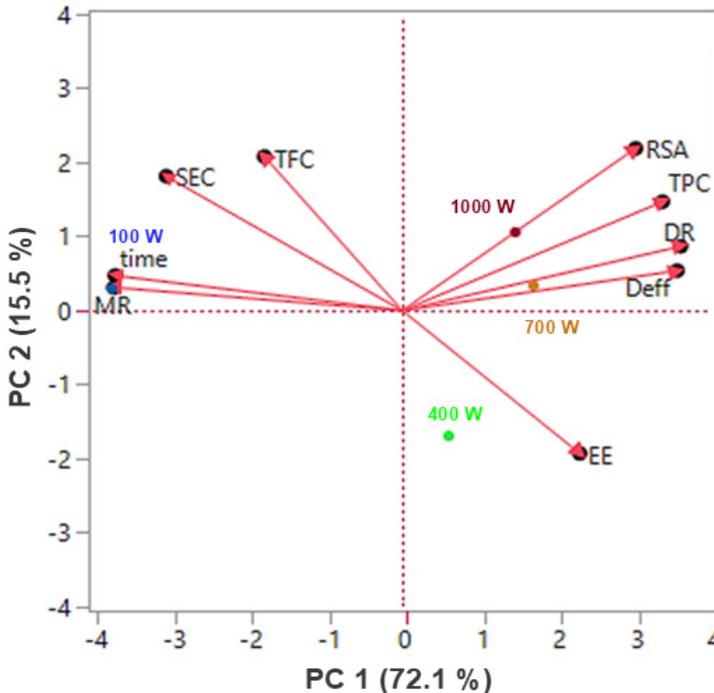
**Figure 4.** Impact of microwave drying power levels on TPC (a), TFC (b), and RSA (c) of olive leaves with different letters indicate significant differences between treatments (ANOVA followed by Tukey's test  $p < 0.05$ ,  $a > b > c$ )

This may be due to the reduced drying time and controlled thermal exposure, which minimize the degradation of bioactive compounds [8]. In contrast, at 100 W, lower antioxidant activity was observed, probably due to insufficient activation of bioactive compounds and potential degradation from prolonged exposure to lower power. Findings align with previous studies indicating that higher microwave power enhances the bioactive potential of plant material leaves [13,37].

### Multivariate statistical analysis

Principal component analysis (PCA) was performed to reduce the dataset's dimensionality and highlight the key relationships among the studied variables (Figure 5). The analysis revealed that the first two components, PC1 and PC2, explained 72.1% and 15.5% of the total variance, respectively, cumulatively accounting for 87.6% of the variance. This high cumulative variance indicates the effectiveness of the dimensionality reduction in capturing the primary patterns within the data.

The loading plot demonstrated that PC1 was predominantly associated with RSA, TPC, and DPPH, all of which showed strong positive loadings. This finding highlights the significant contribution of higher phenolic content to antioxidant activity, consistent with the established role of phenolic compounds as key antioxidants. In contrast, PC2 exhibited weaker associations with TFC and drying time, suggesting that these parameters contributed less to the overall variance.



**Figure 5.** Principal component analysis of drying data for olive leaves  
*Biplot showing the relationships between principal components (PC1 and PC2) and the variables t, MR, DR, Deff, SEC, EE, TPC, TFC, and RSA across microwave power levels.*

The score plot further revealed clear distinctions among samples processed at different microwave power levels. Samples treated at 700 W and 1000 W were clustered in the positive quadrant of PC1, reflecting higher TPC, RSA, and extraction efficiency (EE). These results underscore the benefits of higher microwave power in promoting the extraction of bioactive compounds. Conversely, samples processed at lower microwave power levels (100 W and 400 W) were positioned in the negative quadrants of PC1 and PC2, corresponding to lower phenolic content and antioxidant activity.

Correlations within the dataset further reinforced these trends. RSA exhibited strong positive correlations with TPC and EE, underscoring the role of extraction efficiency in determining antioxidant activity. On the other hand, drying time was negatively correlated with RSA and TPC, indicating that prolonged drying under lower power levels compromised the retention of bioactive compounds.

These findings highlight the importance of rapid, high-power drying techniques in preserving phenolic compounds and antioxidant properties.

## CONCLUSIONS

This study optimized the microwave drying process of olive leaves by balancing drying power, time, bioactive compound preservation, and energy efficiency. The Logarithmic, Modified Henderson, Pabis II, and Hii et al. models demonstrated strong predictive accuracy for drying kinetics. Additionally, a new proposed model showed the best correlation with experimental data, confirmed by high  $R^2$  values and low  $\chi^2$  and RMSE values.

Drying at 700 W and 1000 W preserved bioactive compounds effectively, with significant antioxidant retention. Principal component analysis confirmed that samples dried at these power levels exhibited higher bioactive compound extraction. Among these, 700 W for 21 minutes provided the best compromise, ensuring optimal compound preservation, superior energy efficiency, and economic feasibility. While 1000 W slightly reduced drying time (19 min), 700 W offered a more balanced approach, making it the most advantageous condition.

The novel proposed model holds great potential for designing and optimizing olive leaf drying processes. These findings highlight microwave drying as an efficient and sustainable technique for preserving bioactive compounds, with promising applications in functional foods and phytotherapeutic sciences, reinforcing its industrial relevance.

## EXPERIMENTAL SECTION

### Chemicals and reagents

The reagents and chemicals used in this study were obtained from reputable sources. Folin-Ciocalteu's phenol reagent, sodium carbonate hydrate ( $\text{Na}_2\text{CO}_3$ ), and aluminum chloride reagent ( $\text{AlCl}_3$ ) were obtained from Chimoza (France). Gallic acid and rutin were obtained from Sigma-Aldrich (Germany). Methanol ( $\text{CH}_3\text{OH}$ ), ethanol ( $\text{C}_2\text{H}_5\text{OH}$ ), potassium persulfate, and 2,2-Azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS) were purchased from Biochem-Chemo Pharma (USA).

### Initial moisture content

The initial moisture content ( $M_0$ ) of fresh olive leaves was determined in triplicate. A 15 g sample was heated at  $105 \pm 2^\circ\text{C}$  for 24 hours. The final moisture content was calculated based on the weight loss due to water evaporation, using the dry basis (db) method. This calculation was performed by determining the water weight on a dry basis, as described in Eq. 1.

$$M_{0,db}(\text{g water/g dry matter}) = \frac{W_i - W_f}{W_f} \quad (1)$$

Where  $M_0$  is the initial moisture content (g),  $W_i$  is the initial weight of the sample (g) and  $W_f$  is the final weight of the sample (g).

### Microwave drying experiments

The drying process was conducted using a digital microwave oven (Maxipower MASMO23S) with the following specifications: 230 V and a frequency of 50 Hz. The microwave's internal space measured 483 (W) \* 281 (H) \* 387 (D) mm and included a rotating glass plate with a diameter of 300 mm at the base. Drying experiments were performed at four different power levels: 100, 400, 700, and 1000 W, with both the power output and drying time adjusted via the microwave's digital control system.

During the trials, 15 g samples of olive leaves were arranged in a single layer on a glass plate and placed in the center of the microwave. Moisture loss was periodically assessed by weighing the samples at specific intervals: every 30 seconds at 1000 W, every 1 minute at 700 W, every 2 minutes at 400 W, and every 5 minutes at 100 W. A precision balance (AS 220.R2, Radwag, Radom, Poland) with an accuracy of 0.001 g was used for these measurements. Each experiment was replicated three times, and the average values were recorded. The heating continued until the samples reached equilibrium moisture, indicated by a constant weight of  $7.55 \pm 0.46$  g.

### Mathematical modeling of drying kinetics

Mathematical modeling is essential for accurately simulating drying kinetics and understanding the behavior of drying processes under specific conditions. This study employs 52 mathematical models (Table 3) to identify the most suitable models under varying drying powers. From the initial moisture content of olive leaves, the moisture content data at different time intervals, and the residual moisture contents, the dimensionless moisture ratio was calculated using Eq. 2.

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

Where MR is the moisture ratio,  $M_t$ ,  $M_e$ , and  $M_0$  refer to the moisture content at any time during drying (g H<sub>2</sub>O/g DM), the equilibrium moisture content (g H<sub>2</sub>O/g DM), and the initial moisture content (g H<sub>2</sub>O/g DM), respectively.

Theoretically, equilibrium can only be reached after an infinitely long drying period. As a result, for extended drying times, the equilibrium moisture content ( $M_e$ ) is often disregarded and assumed to be zero. As a result, the moisture ratio can be simplified to Eq. 3 [34].

$$MR = M_t/M_0 \quad (3)$$

**Table 3.** Mathematical models adopted for curve fitting of drying data of olive leaves

	<b>Name</b>	<b>Mathematical equation</b>
1	<i>Ademiluyi Modified</i>	$MR = a \cdot \exp(-kt)^n$
2	<i>Aghbashlo et al.</i>	$MR = \exp(-k_1 t / 1 + k_2 t)$
3	<i>Alibas</i>	$MR = a \exp [(-kt)^n + bt] + g$
4	<i>Balbay and Şahin</i>	$MR = (1 - a) \exp(-kt^n) + b$
5	<i>Chavez-Mendez et al.</i>	$MR = (1 - [1 - L_2] L_1 t)^{1/(1 - L_2)}$
6	<i>Das et al.</i>	$MR = a \cdot \exp(-kt + b \sqrt{t}) + c$
7	<i>Demir et al.</i>	$MR = a \cdot \exp(-kt)^n + b$
8	<i>Diffusion approach</i>	$MR = a \cdot \exp(-kt) + (1 - a) \exp(-kbt)$
9	<i>Fernando and Amarasinghe</i>	$MR = 1 + at + bt^2 / (1 + ct)$
10	<i>Gauss</i>	$MR = a \cdot \exp(-(t+b)^2/2c^2)$
11	<i>Haghi and Angiz – I</i>	$MR = a \cdot \exp(-bt^n) + ct^2 + dt + e$
12	<i>Haghi and Angiz – II</i>	$MR = a + bt + ct^2 + dt^3$
13	<i>Haghi and Angiz – III</i>	$MR = a + bt / (1 + ct + dt^2)$
14	<i>Haghi and Angiz – IV</i>	$MR = a \cdot \exp[-(t - b)^2/2c^2]$
15	<i>Hasibuan and Daud</i>	$MR = 1 - at^n \exp(-kt^m)$
16	<i>Henderson and Henderson I</i>	$MR = c [\exp(-bt) + 1/9 \exp(-9kt)]$
17	<i>Henderson and Henderson II</i>	$MR = c \exp(-bt) + 1/9 \exp(-9kt)$

	<b>Name</b>	<b>Mathematical equation</b>
18	<i>Henderson and Pabis</i>	$MR = a.exp(-kt)$
19	<i>Hii et al.</i>	$MR = a.exp(-kt^n) + b.exp(-gt^n)$
20	<i>Kaleta I</i>	$MR = a.exp(-kt^n) + (1-a).exp(-gt^n)$
21	<i>Khazaei and Daneshmandi</i>	$MR = a + exp(-bt) - ct$
22	<i>Logarithmic (Asymptotic)</i>	$MR = a.exp(-kt) + c$
23	<i>Logistic</i>	$MR = b / (1 + a.exp(-kt)) + kt$
24	<i>Meda et al.</i>	$MR = a.exp(m+n)t^{1.5}$
25	<i>Midilli</i>	$MR = a.exp(-kt^n) + bt$
26	<i>Modifie Henderson and Perry</i>	$MR = a.exp(-kt^n)$
27	<i>Modified drying</i>	$MR = a + exp(-kt^n)$
28	<i>Modified Henderson and Pabis I</i>	$MR = a.exp(-kt) + b.exp(-gt) + c.exp(-ht)$
29	<i>Modified Henderson and Pabis II</i>	$MR = a.exp(-kt^n) + b.exp(-gt) + c.exp(-ht)$
30	<i>Modified Hii et al.</i>	$MR = a.exp(-kt^m) + c.exp(-gt^n)$
31	<i>Modified Midilli I</i>	$MR = exp(-kt^n) + bt$
32	<i>Modified Midilli II</i>	$MR = exp(-kt) + bt$
33	<i>Modified Midilli III</i>	$MR = a.exp(-kt) + bt$
34	<i>Modified Page equation V</i>	$MR = exp[-(kt^n)]$
35	<i>Modified Page equation-III</i>	$MR = exp[-(kt^n)]$
36	<i>Modified Page equation-IV</i>	$MR = a.exp[-(kt^n)]$
37	<i>Modified Page equation-IX</i>	$MR = k.exp[-(t/L^2)^n]$
38	<i>Modified Page equation-VI</i>	$MR = exp(kt^n)$
39	<i>Modified Page equation-VII</i>	$MR = exp[-k.(t/L^2)^n]$
40	<i>Modified Page equation-VIII</i>	$MR = exp\{-[k.(t/L^2)]^n\}$
41	<i>Modified Page II</i>	$MR = exp[-(kt)^n]$
42	<i>Modified Two-term I</i>	$MR = a.exp(-kt) + (1-a).exp(-kat)$
43	<i>Modified Two-term II</i>	$MR = a.exp(kt) + (1-a).exp(-gt)$
44	<i>Verma et al</i>	$MR = a.exp(-kt) + (1-a).exp(-gt)$
45	<i>Two-term exponential</i>	$MR = a.exp(-kt) + a.exp(-gt)$
46	<i>Modified Two-term V</i>	$MR = a.exp(-kt^n) + b.exp(-gt)$
47	<i>Multiple Multiplicative Factor</i>	$MR = (a.b + c.t^d) / (b + t^d)$
48	<i>Newton</i>	$MR = exp(-kt)$
49	<i>Page</i>	$MR = exp(-kt^n)$
50	<i>Parabolic</i>	$MR = c + bt + at^2$
51	<i>Peleg</i>	$MR = 1 - t/(a + bt)$
52	<i>Regression I</i>	$MR = exp(-(at^2 + bt))$
53	<i>Proposed model</i>	$MR = a + b.exp(-k_1t) + c.exp(-k_2t)$

*k.*  $k_0$ .  $k_1$ .  $k_2$ . *g:* drying coefficients (1/min); *a.* *b.* *c.* *d.* *e.* *L.*  $L_1$ .  $L_2$ : coefficients of the equations;  $n$ .  $m$ : exponent; *t* - time (min); *L:* half of thickness (m)

### Drying rate

The drying rate (DR) of olive leaves at different powers was calculated using Eq. 4.

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (4)$$

Where DR is the drying rate (g H<sub>2</sub>O/g DM), M<sub>t + dt</sub> is the MC at t + Δt (g H<sub>2</sub>O/g DM), M<sub>t</sub> is the moisture content (MC) at t (g H<sub>2</sub>O/g DM), and dt is the difference in drying time (min).

The relationship between DR and time was analyzed through graphical plots to assess the drying behavior.

### Effective moisture diffusivity

Effective diffusivity quantifies a material's ability to facilitate moisture movement from its interior to the surface, where evaporation occurs. This is based on thermodynamics and fluid kinetics, especially Fick's second law [38]. Understanding and measuring D<sub>eff</sub> is essential for optimizing drying conditions, improving energy efficiency, and ensuring product quality. To calculate D<sub>eff</sub>, the analytical solution of Fick's second law (Eq. 5) was applied, as described by Crank [39].

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left( D_{eff} \frac{\partial M}{\partial x} \right) \quad (5)$$

For extended drying periods, Eq. 6 can be simplified by considering only the first term of the series, resulting in Eq. 7.

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

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

where D<sub>eff</sub> represents the effective moisture diffusivity (m<sup>2</sup>/s), L refers the sample thickness (L = 2.211 × 10<sup>-3</sup> m), and t represents the drying time (s)

A logarithmic form, Eq. 8, was therefore introduced, applicable when moisture diffusivity remains constant at each drying temperature, resulting in a linear relationship between the logarithmic moisture ratio and drying time. However, in our case, the experimental logarithmic drying curve is not linear. This suggests that the effective moisture diffusivity depends on moisture content, which is common for highly porous materials [20].

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

The plot of  $\ln(MR)$  against drying time should produce a straight line with the following slope:

$$Slope = \left( \frac{\pi^2}{4L^2} D_{eff} \right) \quad (9)$$

Therefore, Eq. 10 is evaluated numerically for the Fourier number  $F_0$  for diffusion.

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

The effective moisture diffusivity was determined using Eq. 11 [40].

$$D_{eff} = \frac{F_0}{\left( \frac{t}{4L^2} \right)} = \frac{-0.101 \ln(MR) - 0.0213}{\left( \frac{t}{4L^2} \right)} \quad (11)$$

### Activation energy

The activation energy ( $E_a$ ) for the diffusion process during drying represents the energy required to initiate the movement of water from the material during the drying process [26], which describes the relationship between the  $D_{eff}$  and temperature. In microwave-assisted drying processes, the Arrhenius equation is often modified to incorporate the power of the microwave. [31] use the correlation between the effective diffusion coefficient and microwave power ( $m/P$ ) to calculate  $E_a$ , as shown in Eq. 12.

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

Where  $E_a$  is the activation energy (W/g),  $m$  is the mass of the raw sample (g),  $D_{eff}$  is the effective diffusivity ( $m^2/s$ ),  $D_0$  is the pre-exponential factor ( $m^2/s$ ),  $P$  is the power (W).

### Energy consumption

Energy consumption during the drying process is a critical parameter that directly impacts the efficiency and cost-effectiveness of dehydration techniques, especially microwave drying. In this study, the energy consumption for drying olive leaves was assessed using specific energy consumption and electrical energy efficiency metrics. The energy consumption required for the microwave drying was directly measured using a wattmeter (PEREL, E305EM6, Germany).

Specific electric energy consumption was determined using Eq. 13 to quantify the energy used to remove a kilogram of water from the sample. This index is crucial for assessing the efficiency of the drying process and optimizing energy usage.

$$SEC \left( \frac{\text{MJ}}{\text{kg H}_2\text{O}} \right) = \frac{3600 E}{M_s(X_i - X_f)} \quad (13)$$

Where SEC is specific energy consumption, represented (kWh/kg water removed), E is the total energy consumed (kWh), and  $M_s (X_i - X_f)$  is the mass of water removed (kg).

Additionally, electrical energy was calculated using Eq. 14 to evaluate the proportion of energy effectively used to evaporate the water content from the sample.

$$EE (\%) = M_s(X_i - X_f) \frac{\Delta h_v}{3600 \times E} \times 100 \quad (14)$$

where EE is the electrical energy efficiency (%),  $M_s (X_i - X_f)$  is the mass of water removed (kg),  $\Delta h_v$  is the enthalpy of evaporation of water (2257 kJ/kg at 100°C), and E is the total energy consumed (kWh).

### Ultrasonic-assisted extraction of bioactive compounds

To extract the bioactive compounds from dried olive leaves at different powers, 2 g of olive leaf powder were combined with 25 mL of a 70:30 (v/v) ethanol-water. The mixture was subjected to ultrasound treatment with an ultrasonic bath (UCI-150, R. Espinar SL, Barcelona, Spain) operating at 40 kHz and a power of 400 W. The extraction was performed at 45°C for 10 minutes. The sample was centrifuged at 5000 × g for 10 min at 4°C, using a SIGMA 3–30K centrifuge (Germany), and the supernatant was recovered. The remaining pellet was reextracted using the same volume of solvent under the same conditions, and the extracts were combined. Ethanol was removed using a rotary evaporator, and the aqueous phase was subsequently lyophilized to obtain the dry extract.

### Total phenolic content (TPC)

TPC of the olive leaf extracts was determined using the Folin-Ciocalteu method [41]. A 20 µL aliquot of the diluted extract was mixed with 100 µL of Folin-Ciocalteu reagent (diluted 1:10 with distilled water) and 80 µL of sodium carbonate solution (7.5%). The mixture was incubated at room temperature for 30 min, and the optical density was measured at 760 nm using a microplate reader (BioTek Synergy HTX). Results were expressed as gallic acid equivalents (mg GAE/g DM).

### Total flavonoid content (TFC)

The aluminum chloride method determined the total flavonoid content [42]. A 100  $\mu\text{L}$  aliquot of the diluted extract was mixed with 100  $\mu\text{L}$  of  $\text{AlCl}_3$  solution (2% in ethanol). After incubation at room temperature for 10 min, the absorbance was measured at 430 nm using a microplate reader. Results were expressed as rutin equivalents (mg RE/g DM).

### Radical scavenging activity (RSA)

The ABTS assay was used to determine the antioxidant capacity of olive leaf extracts [43]. The ABTS radical cation was generated by reacting 7 mM ABTS with potassium persulfate and incubating the mixture in the dark for 12 hours. The resulting  $\text{ABTS}^{+\cdot}$  solution was diluted with ethanol to achieve an absorbance of  $0.70 \pm 0.02$  at 734 nm. A 20  $\mu\text{L}$  aliquot of the diluted olive leaf extract was mixed with 180  $\mu\text{L}$  of the  $\text{ABTS}^{+\cdot}$  solution. After a 10-minute incubation period, the absorbance was measured at 734 nm using a microplate reader (BioTek Synergy HTX). The scavenging potential of the extracts was quantified as milligrams of gallic acid equivalent per gram of dry matter (mg GAE/DM).

### Data analysis

Mathematical modeling and statistical analyses were performed using STATISTICA software 10.0. Drying kinetics were modeled through nonlinear regression, and the software provided key parameters, including the Root Mean Square Error (RMSE) using Eq. 15, coefficient of determination ( $R^2$ ) derived from Eq. 16, and chi-square ( $\chi^2$ ) using Eq. 17. A new drying kinetics model was proposed and validated using JMP® Pro 14.0.0 software (SAS Institute Inc., USA) employing nonlinear regression and model optimization, along with Microsoft Excel (Microsoft Office 2019, USA) for additional data processing. Statistical significance was assessed using one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test, with a significance level set at  $P < 0.05$  [20].

$$RMSE = \sqrt{\sum_{i=1}^N \frac{(MR_{pre,i} - MR_{exp,i})^2}{N}} \quad (15)$$

$$R^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - \overline{MR}_{exp})^2 (MR_{pre,i} - \overline{MR}_{pre})^2}{\sum_{i=1}^N (MR_{exp,i} - \overline{MR}_{exp})^2 \sum_{i=1}^N (MR_{pre,i} - \overline{MR}_{pre})^2} \quad (16)$$

$$\chi^2 = \sum_{i=1}^N \frac{(MR_{pre,i} - MR_{exp,i})^2}{N - Z} \quad (17)$$

Where,  $MR_{exp,i}$  is the experimental moisture ratio at observation,  $MR_{pre,i}$  is the predicted moisture ratio at this observation,  $N$  is the number of experimental data points, and  $Z$  is the number of coefficients and constants.

Principal component analysis was conducted using XLSTAT software to assess a range of variables, including drying time, MR, DR,  $D_{eff}$ , SEC, EE, TPC, TFC, RSA.

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## SUPPORTING INFORMATION

Appendix A is available to download: <https://doi.org/10.5281/zenodo.19102031>

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