Journal of Food Technology Research
2026 Vol. 13, No. 2, pp. 46-64
ISSN(e): 2312-3796
ISSN(p): 2312-6426
DOI: 10.18488/jftr.v13i2.4931
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Drying kinetics, energy use, and functional quality of lemon slices in convective, microwave, and hybrid systems

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Article History
Received: 28 July 2025
Revised: 21 January 2026
Accepted: 18 February 2026
Published: 23 April 2026

Keywords
Drying kinetics
Energy efficiency
Functional quality
Lemon slices
Mathematical modeling.

ABSTRACT

The present study investigated the drying behavior and quality attributes of lemon slices subjected to three drying techniques: convective drying (CD), microwave drying (MD), and combined microwave-convection drying (CMD). The major objectives were to assess drying kinetics, energy efficiency, and the preservation of functional quality. Parameters such as drying time, drying rate, effective moisture diffusivity, specific energy consumption, energy efficiency, color retention, and the stability of bioactive compounds were evaluated. Twenty-two mathematical models were fitted to the experimental data and evaluated using three statistical criteria (R^2, χ^2, and RMSE). The best-performing model provided the closest fit to the drying kinetics of lemon slices, with $0.9923 \leq R^2 \leq 0.9995$, $3.90\times10^{-5} \leq \chi^2 \leq 6.21\times10^{-4}$, and $5.99\times10^{-3} \leq \text{RMSE} \leq 2.47\times10^{-2}$ across all drying conditions. CMD and MD reduced drying time by more than 80% compared to CD, while CMD increased the effective moisture diffusivity by approximately 70%. Specific energy consumption decreased by up to 60% under CMD and MD, with microwave drying at 900 W demonstrating the highest energy efficiency. CMD also ensured better retention of phenolic compounds and antioxidant activity, and it resulted in up to 50% less color degradation compared to CD. The integrated system enabled real-time monitoring of drying and moisture dynamics, facilitating accurate prediction of drying behavior and product quality. Overall, the study demonstrated that CMD offers an optimal balance between preserving product quality and enhancing drying efficiency, making it a scalable and sustainable solution for industrial lemon drying processes.

Contribution/Originality: This study provides one of the initial comparative assessments of convective, microwave, and hybrid drying methods for lemon slices. The developed hybrid system enabled in-situ moisture monitoring in real-time, demonstrating the benefits of combined microwave drying (CMD) for improving energy efficiency and maintaining product quality.

1. INTRODUCTION

Citrus fruits are among the most widely consumed fruits worldwide due to their rich nutritional profile and health benefits (Bozkir, 2020). Global citrus production has significantly expanded, and lemon (Citrus limon L.) is one of the most important species. According to recent FAO data (FAO, 2025), global lemon production increased from approximately 8.07 million tonnes in 1994 to over 23.64 million tonnes in 2023, demonstrating the rapid growth of this industry. Lemons are highly valued for their nutrient and bioactive profiles. They serve as a major source of vitamin C, organic acids, dietary fiber, essential oils, and minerals. Additionally, they are rich in bioactive compounds with antioxidant potential, such as carotenoids (α- and β-carotene, β-cryptoxanthin), polyphenols (phenolic compounds, hydroxycinnamic acid derivatives), and flavonoids (flavanones, flavones, flavonols). These compounds have been shown to provide various health benefits, including antioxidant, anti-inflammatory, antiviral, and anticancer activities (Kesbi, Sadeghi, & Mireei, 2016). The protective role of these natural compounds against chronic diseases, including cardiovascular disorders, cancer, and age-related diseases, has also been studied (M'hiri, Ghali, Nasr, & Boudhrioua, 2018).

Lemon fruits are marketed fresh and are also processed to extract juice, essential oils, fiber, and pectin (Ghanem, Bonazzi, Kechaou, & Mihoubi, 2015; M'hiri et al., 2018). These treatments can also produce waste that can be transformed into by-products for high-value applications, including the extraction of bioactive compounds, the production of bioethanol, and the recovery of pectins (Agoda-Tandjawa, Mazoyer, Wallecan, & Langendorff, 2020; Mamma & Christakopoulos, 2014). Despite their value, lemons are considered to have a high moisture content of 80-90%, making them highly perishable (M'hiri et al., 2018), thus requiring efficient preservation to extend shelf life with retention of nutritional values. Drying is still considered one of the better methods for reducing moisture that facilitates the growth of microorganisms responsible for microbial spoilage, and thus enables material to be stored and transported (Ali et al., 2020; Mouhoubi, Boulekbache-Makhlouf, Mehaba, Himed-Idir, & Madani, 2022). However, conventional convective drying (CD), though widely applied in more than 85% of food products (Boateng, 2024), has some drawbacks, such as degradation of nutrients and high energy consumption (Ashtiani et al., 2020). Advanced methods have been developed to transcend these limits: microwave drying and microwave-assisted convective drying. Microwave drying enables fast volumetric heating and improved energy efficiency; additionally, microwave-assisted drying combined with convective drying processes offers several advantages. These include reduced drying time, lower energy consumption, and better retention of the fruit's nutrients and antioxidant properties (Calin-Sanchez et al., 2020; Kaveh, Abbaspour-Gilandeh, & Nowacka, 2021; Yildiz & İzli, 2019).

This study addresses an important research gap by comparing the drying of lemon slices using CD, MD, and CMD methods. Although extensive research has been conducted on the drying of citrus fruits, few studies have collectively compared these methods or applied comprehensive mathematical modeling to assess moisture diffusion and quality changes. The drying experiments evaluated drying kinetics, energy efficiency, moisture diffusivity, and the retention of phenolic compounds, antioxidants, and color attributes. Mathematical modeling was employed to fit experimental data and identify the most accurate predictive model for describing lemon slice drying kinetics. The validated models provided enhanced insights into moisture migration and process performance, enabling process optimization, real-time monitoring, and improved quality control. The findings offer valuable understanding of heat and mass transfer mechanisms and support the development of sustainable, energy-efficient, and scalable drying technologies for high-quality food production.

2. MATERIAL AND METHODS

2.1. Raw Material

Fresh lemon (*Citrus limon L.*), Eureka variety, with an initial moisture content (wet basis) of 86.25 ± 0.34 %, was purchased from a local market in Batna, Algeria. The lemon fruits were selected based on their ripeness, uniform shape and size, consistent color, and absence of blemishes or damage. After cleaning, the lemon fruits were stored in

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a refrigerator at 4°C with 90% relative humidity throughout the experimental period. Before drying, the lemons were sliced into thin slices using an electric slicer with a rotating disc blade (Star Bake FP350, China), with the slices' thickness measured at 5 ± 0.01 mm using a caliper.

2.2. Drying Equipment and Drying Procedure

Drying experiments were performed using a custom-built pilot-scale system that combined a domestic microwave oven (LG-MC7647B, LG Electronics Inc.) with max output (900W at 2.45 GHz) with a hot-air convection unit (Figure 1). The microwave cavity, with a volume of 0.028 m³, served as the primary drying chamber. Heated air was introduced into the system through a blower and passed through three 2.25 kW electric heating coils. Air velocity was maintained at 1.5 m/s using a control valve, while temperature was monitored by T-type thermocouples and regulated with a digital thermostat (L. Controls 16A, USA). Hot air entered the drying chamber from the bottom, where it interacted with microwave energy to facilitate drying. Lemon slices were placed on a perforated tray suspended from a precision digital balance (Sartorius B3100S, ± 0.01 g), enabling real-time monitoring of moisture loss. Moist air was continuously evacuated by an exhaust fan at the chamber outlet.

Three drying methods were tested: microwave drying (MD) at 180, 540, and 900 W; convective drying (CD) at 50, 60, and 70°C; and combined microwave-convective drying (CMD) at 540 W with air temperatures of 50, 60, and 70°C. The 540 W power level was selected for CMD based on preliminary evaluations of energy efficiency and product quality. For each experiment, approximately 130 g of lemon slices were arranged in a thin, even layer. All drying trials were conducted in triplicate, and drying was continued until a constant weight was observed, allowing accurate determination of moisture content over time.

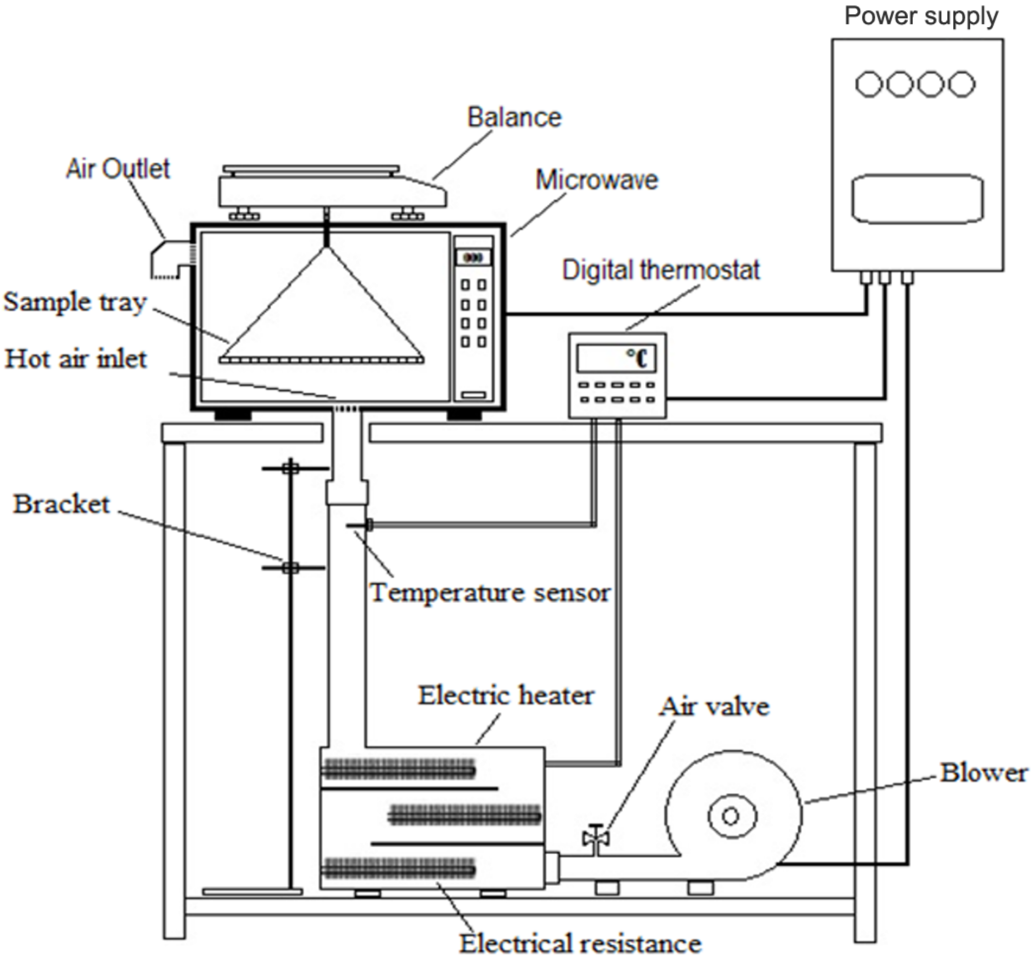

Figure 1. Schematic of the drying system, the Microwave-assisted Hot-air dryer.

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2.3. Mathematical Modeling

Mathematical modeling was reported to fit the experimental data obtained during the drying of lemon slices using nonlinear regression analysis. For this purpose, twenty-two different mathematical models (Table 1) that are frequently used to identify the best-fitting model capable of accurately describing the drying behavior of lemon slices under various drying conditions were evaluated.

These models, used to estimate the response of drying curves, employ equations that describe the moisture ratio as a function of drying time. A dimensionless moisture ratio, denoted as MR, is considered, applying the following Equation 1.

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

Where: M_t is the moisture content at time t during drying, M_0 and M_e are the initial and equilibrium moisture contents (kg water per kg dry matter), respectively. However, M_e values are insignificant compared to M_t and M_0 (Ye et al., 2021) and the moisture ratio (MR) was simplified to Equation 2.

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

The drying rate versus time graph can provide insights into the drying behavior (Aral & Bese, 2016). The drying rate (DR) at any given time was calculated using Equation 3.

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

Where: DR is the drying rate (kg water per kg dry matter per minute), M_{t+dt} is the moisture content (MC) at t+dt (kg water per kg dry matter), M_t is the MC at time t (kg water per kg dry matter), and dt is the difference in drying time (minutes).

Table 1. Mathematical thin-layer models selected for drying-kinetics modeling of lemon slices.

Model name	Model equation
Newton	$MR = \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Modified Page 1	$MR = \exp(-(kt)^n)$
Henderson and Pabis (1961)	$MR = a.\exp(-kt)$
Logarithmic	$MR = a.\exp(-kt)+c$
Logistic	$MR = b/(1+a.\exp(k.t))$
Śledź, Nowacka, Wiktor, and Witrowa-Rajchert (2013)	$MR = b.\exp(-kt)/(1+a.\exp(k_1.t))$
Modified Page 2	$MR = \exp(-kt)^n$
Midilli, Kucuk, and Yapar (2002)	$MR = a.\exp(-kt^n)+bt$
Two terms	$MR = a.\exp(-kt)+b.\exp(-k_1t)$
Two terms exponential	$MR = a.\exp(-kt)+(1-a).\exp(-kat)$
Approximation of diffusion	$MR = a.\exp(-kt)+(1-a).\exp(-kbt)$
Verma, Bucklin, Endan, and Wratten (1985)	$MR = a.\exp(-kt)+(1-a).\exp(-k_1t)$
Modified Henderson and Pabis (1961)	$MR = a.\exp(-kt)+b.\exp(-k_1t)+c.\exp(-k_2t)$
Parabolic	$MR = a+b.t+c.t^2$
Wang and Singh (1978)	$MR = 1+a.t+b.t^2$
Fernando and Amarasinghe (2016)	$MR = (1+a.t+b.t^2)/(1+c.t)$
Chávez-Méndez, Jiménez-Munguía, Salgado-Cervantes, and Luna-Solano (2012)	$MR = (1-(1-L_2)L_1t)^{1/(1-L_2)}$
Demir, Gunhan, Yagcioglu, and Degirmencioglu (2004)	$MR = a.\exp(-kt)^n+b$
Weibull	$MR = \exp(-(t/a)^b)$
Dinani, Hamdami, Shahedi, and Havet (2014)	$MR = a.\exp(-((t-b)/a)^2)$
Simplified Fick's diffusion equation	$MR = a.\exp(-k(t/L^2))$

Note: MR, moisture ratio; a, b, c, L_1, L_2, coefficients; k, k_1, k_2, drying coefficients (1/min); n, exponent specific to each equation; t, time; L, half of thickness.

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2.4. Effective Moisture Diffusivity Determination

Various internal transfer mechanisms of mass in porous materials during the drying process exist. However, one of the primary mechanisms is the effective moisture diffusivity (D_{eff}), which describes the transport of moisture to the surface for evaporation (Aral & Bese, 2016; Joardder, Akram, & Karim, 2021). Fick's second law of unsteady state diffusion was used to determine the moisture diffusivity D_{eff} of lemon slices, assuming the initial moisture content is uniform, infinite slab geometry, diffusion coefficient is constant and a negligible external mass transfer resistance, the diffusion model can be simplified to a logarithmic form (Equation 4).

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

Where: D_{eff} is the effective moisture diffusivity (m^2s^{-1}), L is the half-thickness (L=0.0025 m) of thin-layer lemon slices (drying occurred on two faces), and t is the drying time (s). The slope of the linear regression of ln (MR) versus drying time was used to calculate D_{eff}.

The derivation and simplification of Fick's second law into a linearized form relating the moisture ratio (*MR*) to drying time (*t*) for determining D_{eff} are provided in Table A (Appendix).

2.5. Energy Consumption

The energy consumption can be assessed using two different efficiency indices, which are the specific electrical energy consumption SECe (MJ/kg H_2O) and the energy efficiency EE (%), and are calculated using the equations (Wang, Zhang, & Mujumdar, 2014).

$$SEC_e = \frac{3600E}{M_s(X_i - X_f)} \qquad (5)$$

Where, SEC_e represents the Specific Electrical Energy Consumption (MJ/kg H_2O), E is the overall electrical energy consumption (kWh), Ms is the amount of dry solid matter (kg), and (X_i and X_f) represent the initial and final moisture contents (d.b), respectively.

$$EE = M_s(X_i - X_f)\frac{\Delta h_v}{3600E}.100 \qquad (6)$$

Where Δhv is the water's evaporation enthalpy (2257 kJ/kg, at 100°C) and EE is the energy efficiency (%).

2.6. Physicochemical Properties

2.6.1. Extraction Procedure

Total phenolic compounds from the lemon powders were extracted using the method of Dahmoune, Nayak, Moussi, Remini, and Madani (2015) with slight modifications. Briefly, 1 g of lemon powder from each drying process was added to 40 mL of 50% ethanol (v/v) and then treated for 30 min with acoustic waves using an ultrasonic processor (Sonics VCX 500, Connecticut, USA). After ultrasonic extraction, all the extracts were filtered at room temperature using Whatman No. 1 filter paper, and the filtered supernatants were stored at 4°C until analysis. The extraction was performed in triplicate for all samples.

2.6.2. Total Phenolic Content (TPC) Determination

Total phenolic in lemon was quantified by the Folin–Ciocalteu (Jaramillo-Flores et al., 2003). 0.1 mL of the supernatant was mixed with 0.75 mL of a tenfold diluted Folin–Ciocalteu reagent and incubated at room temperature for 5 min; 0.75 mL of 6% sodium bicarbonate (Na2CO3) solution was added to the mixture and left standing at room temperature for 90 min before spectrophotometric analysis. The absorbance of extracts was measured at 725 nm

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using a UV-2600 spectrophotometer (Shimadzu, Japan). TPC was expressed as mg gallic acid equivalents (GAE) per gram of powder on a dry weight (DW) basis ± standard deviation for three triplicates.

2.6.3. Total Flavonoid Contents (TFC) Determination

Total flavonoid content of the extracts was determined according to Quettier-Deleu et al. (2000) using AlCl3 method. Briefly, 1 ml of supernatant was mixed with 1 ml of 2% aluminium chloride methanol solution. The mixture was left to stand for 10 minutes before spectrophotometric analysis. The specific absorbance at 430 nm was measured using a UV-2600 spectrophotometer (Shimadzu, Japan) and was compared with a quercetin standard curve for estimating total flavonoids in the extracts. The TFC was expressed in mg quercetin equivalent (QE) per gram of powder on dry weight (DW) ± the standard deviation of three triplicates.

2.6.4. Antioxidant Activity Determination

The antioxidant activity of lemon extracts was assessed through two radical scavenging assays: DPPH and ABTS. The DPPH assay was performed according to Brand-Williams, Cuvelier, and Berset (1995). Briefly, 10 µL of the extract supernatant was mixed with 300 µL of a DPPH solution (63 µM in methanol). The mixture was incubated at 37°C in the dark for 20 minutes. After incubation, the absorbance was measured at 515 nm. All measurements were performed in triplicate, and the results were expressed as a percentage of inhibition, calculated using the equation (Equation 7).

$$AOX = \%Inhibition = \frac{A_{control} - A_{sample}}{A_{control}} \times 100 \qquad (7)$$

Where $A_{control}$ is the absorbance of the DPPH solution without extract and A_{sample} is the absorbance after interaction with the extract.

The ABTS assay was performed according to Quan et al. (2023). A radical solution was created by blending 7 mM ABTS with 2.45 mM potassium persulfate in ethanol, and incubated in the dark for 12–16 hours to form the $ABTS^{\bullet+}$ radical. The solution was diluted with ethanol to an absorbance of 0.70 ± 0.03 at 734 nm before conducting the assay. For the assay, 1 mL of the $ABTS^{\bullet+}$ solution was added to 0.01 mL of dilution (1:5) of lemon extract before incubating in the dark for 6 minutes and recording the absorbance at 734 nm. Antioxidant activity calculations were conducted as a percentage of inhibition using the same calculation (Equation 8).

$$AOX = \%Inhibition = \frac{A_{control} - A_{sample}}{A_{control}} \times 100 \qquad (8)$$

Where $A_{control}$ is the absorbance of the $ABTS^{\cdot +}$ solution without extract and A_{sample} is the absorbance after reaction with the extract.

2.6.5. Color Evaluation

Colorimetric parameters of fresh and dried lemon under different conditions were measured using a colorimeter (Konica Minolta CR-10, Japan). Color values were expressed as CIE coordinates L^* (whiteness or brightness), b^* (yellowness/blueness), and a^* (redness/greenness), which were used to describe the color of the samples (M’hiri et al., 2018). The results are the average of six replicate measurements and the total color difference (ΔE) was calculated according to the following equation (Eq. 9) where, the subscript "0" in the equation mentions the control values for fresh lemon.

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$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (9)$$

2.7. Goodness of Fit Statistics

To ascertain the appropriateness of experimental data, each experiment was performed in triplicate, and data were reported as means ± standard deviation. Data were statistically compared using an analysis of variance (ANOVA) in Minitab software (Minitab, version 21.3.1, USA). Trends were statistically considered significant when data sets compared had means that differed at $p \leq .05$ (Tukey's test). Model equations represented the goodness of fit of experimental drying data; the coefficients included the correlation coefficient (R^2), root mean square error (RMSE), and chi-square (χ^2). A nonlinear regression analysis and kinetic modeling were completed using STATISTICA software 8.0 (StatSoft Inc., USA). The best model had the highest R^2 values and the lowest χ^2 and RMSE (Izli, Yıldız, Ünal, Işık, & Uylaşer, 2014; Zhang et al., 2015). These parameters are calculated as follows.

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{pre,i} - MR_{\exp,i})^2}{N - z} \quad (10)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (MR_{pre,i} - MR_{\exp,i})^2}{N}} \quad (11)$$

Where $MR_{exp,i}$ is the experimental moisture ratio, $MR_{pre,i}$ is the predicted moisture ratio, N is the number of observations, and z is the number of constant parameters.

3. RESULTS AND DISCUSSIONS

3.1. Drying Kinetics

The mass losses of the samples during the three applied processes, microwave drying (MD), convective drying (CD), and combined microwave-convective drying (CMD), are presented as drying curves (Figure 2a, b, c, respectively). These curves illustrate the variations in moisture ratio over time under specific drying conditions, including microwave power levels (180, 540, and 900 W) and inlet hot air temperatures (50, 60, and 70°C).

The results reveal a rapid moisture loss during the initial drying stage, followed by a gradual decline until the samples reached their final moisture content. Notably, no constant-rate drying period was observed; instead, all drying processes occurred exclusively in the falling-rate period. This suggests that moisture transfer within the lemon slices was predominantly governed by diffusion. Similar trends have been reported in previous studies (Deepika & Sutar, 2018; Mouhoubi et al., 2022; Tarafdar, Jothi, & Kaur, 2021; Xie, Gao, Liu, & Xiao, 2017).

As shown in Table 2, increasing the drying air temperature significantly reduced drying time. The time required to reach a final moisture content (MC) of approximately 8% (w.b.) was 1350, 1140, and 720 minutes at 50°C, 60°C, and 70°C, respectively. These findings align with earlier studies reporting a direct correlation between higher temperatures and shorter drying durations (Ismail, Kipcak, & Doymaz, 2019; Nguyen, Van Vuong, Bowyer, Van Altena, & Scarlett, 2015; Siabdallah, Laabed, Ferhat, Lahbari, & Fahloul, 2023). Despite this improvement, CD remains relatively time-consuming compared to other techniques.

MD significantly shortened drying time. The duration to achieve the final MC was 84, 30, and 19.5 minutes at 180, 540, and 900W, respectively. This reduction is attributed to rapid internal heating from microwave energy, which creates a vapor pressure gradient between core and surface, enhancing the mass transfer, as reported by Darvishi, Khoshtaghaza, and Minaee (2014). Similar results were reported by Agbede et al. (2020), Alibas and Kacar (2016) and Yilmaz, Demirhan, and Özbek (2021) where they obtained comparable MD results using different food materials. Such results can be explained, in part, by the advantage of short processing times, which is one of the benefits of the MD process.

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CMD further enhanced drying efficiency. At 540W, raising air temperature from 50 to 70°C reduced the drying time from 32.5 to 16.5 minutes. Such a hybrid method couples microwave rapid internal heating with efficient surface evaporation by convection. Kesbi et al. (2016) showed that the microwave-convective drying method reduced the drying time of lemon slices by about 20 to 30 times compared to a convective drying process. The results obtained confirm previous reports on the drying behavior of various types of fruits and vegetables (Mouhoubi et al., 2022; Quan et al., 2023; Torki-Harchegani, Ghasemi-Varnamkhasti, Ghanbarian, Sadeghi, & Tohidi, 2016). CMD achieved the fastest drying, confirming its superiority over MD and CD in reducing drying time and enhancing process efficiency through synergistic heat and mass transfer.

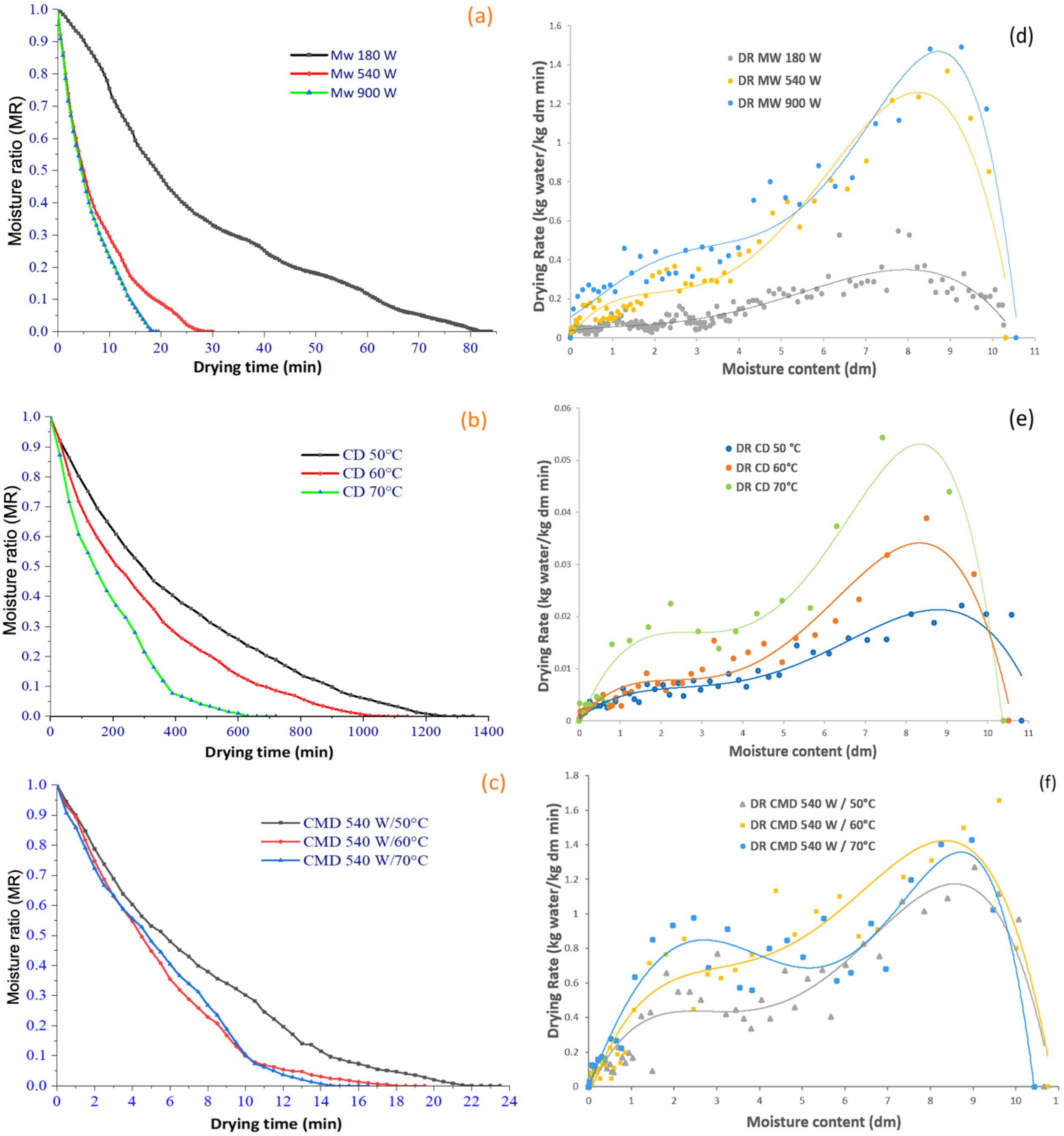

Figure 2. Drying kinetics and drying rate curves of lemon slices under different drying methods: (a, d) MD Microwave drying, (b, e) CD Convective drying, and (c, f) CMD Combined microwave-convective drying. Panels (a–c) show the drying kinetics, and panels (d–f) represent the drying rate versus moisture content.

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3.2. Drying Rate Evolution versus Moisture Content

The drying rate variation as a function of moisture content for lemon slices subjected to three different drying processes CD, MD, and CMD is illustrated in Figure 2.

In MD and CD (Figure 2d, e, respectively), the drying process exhibits two distinct phases: an initial constant-rate period, followed by a falling-rate period beginning once the moisture content reaches a critical threshold. In contrast, the drying rate curves of the CMD method (Figure 2f) display only a single falling-rate period after a brief warm-up phase characterized by high drying rates. This warm-up period is more noticeable in CMD due to its significantly shorter drying duration. In the case of CD, a longer drying time means it comprises a smaller part of the entire process and therefore is less distinct on the drying rate curves. These findings are consistent with previous studies that focus on microwave-assisted drying (Deepika & Sutar, 2018; Doymaz, Kipcak, & Piskin, 2015; Guemouni et al., 2022).

Drying of most biological matrices falls within the falling-rate period, according to Agbede et al. (2020). According to Kesbi et al. (2016), this phase involves two main mechanisms: internal moisture movement toward the surface and surface moisture evaporation. The efficiency of both internal and external mechanisms depends on the drying method applied (i.e., MD cannot rely on airflow as external resistance, while CD is greatly limited by high internal resistance to internal moisture migration). Therefore, combining both techniques improves mass transfer and shortens drying time.

During the initial drying phase, high moisture content in lemon slices promotes greater microwave absorption and higher drying rates due to enhanced moisture diffusion. As drying proceeds, reduced moisture content decreases microwave energy absorption, leading to a decline in drying rates. This supports the findings of Alibas and Kacar (2016) who reported that microwave power has a stronger influence on drying rates than air temperature in CD.

Drying rates vary significantly across the three methods. As shown in Table 2, CD achieved average drying rates of 0.01- 0.02 kg water/kg dm min at 50 - 70°C. The MD showed increased rates between 0.13 and 0.55 kg water/kg dm min across 180 - 900 W. The CMD yielded the highest rates, ranging from 0.46 to 0.64 kg water/kg dm min at 540 W and 50 - 70°C, confirming previous results on the benefits of CMD, as reported by Darvishi et al. (2014); Doymaz et al. (2015); Monteiro, Carciofi, and Laurindo (2016) and Torki-Harchegani et al. (2016).

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Table 2. Kinetic parameters (Drying time, DR and Deff), energy consumption (SECe and EE) and phytochemical quality (TFC, TPC, DPPH and ABTs) of dried lemon slices at different drying conditions.

	Convective drying			**Microwave drying**			**Combined Microwave-Convective Drying**		
	50 °C	**60°C**	**70°C**	**180 W**	**540 W**	**900 W**	**540W/50°C**	**540W/60°C**	**540W/70°C**
Time (min)	1350 ±30^{e}	1140 ±30^{d}	720 ±10^{c}	84 ±20^{b}	30 ±10^{a}	19.50 ±0.71^{a}	23.5 ±0.71^{a}	19.4 ±0.60^{a}	16.5 ±0.70^{a}
DR (Kg water/Kg dm min)	0.01 ±0.01^{a}	0.01 ±0.00^{a}	0.02 ±0.00^{a}	0.13 ±0.00^{b}	0.35 ±0.01^{c}	0.55 ±0.01^{e}	0.46 ±0.01^{d}	0.58 ±0.03^{e}	0.64 ±0.02^{f}
D_{eff} (x10^{-10} m^2/s)	0.95 ±0.01^{a}	1.45 ±0.36^{a}	2.12 ±0.06^{a}	9.66 ±2.02^{b}	43.73 ±1.13^{c}	48.7 ±1.91^{d}	57.42 ±0.94^{e}	61.12 ±0.59^{e}	69.13 ±2.26^{f}
SEC_e (x10^{+7} MJ /kg H_2O)	11.77 ±0.51^{d}	9.69 ±0.06^{c}	6.06 ±0.04^{b}	0.48 ±0.00^{a}	0.17 ±0.00^{a}	0.11 ±0.01^{a}	0.34 ±0.01^{a}	0.28 ±0.01^{a}	0.23 ±0.01^{a}
EE (x10^{-2} %)	0.19 ±0.01^{a}	0.23 ±0.00^{a}	0.37 ±0.00^{a}	4.69 ±0.04^{b}	13.15 ±0.28^{f}	19.96 ±0.15^{g}	6.73 ±0.11^{c}	8.06 ±0.22^{d}	9.76 ±0.21^{e}
TFC (mg QE/g)	0.64 ±0.32^{a}	0.81 ±0.27^{ab}	1.07 ±0.24^{abcd}	0.87 ±0.43^{abc}	1.46 ±0.22^{bcd}	1.73 ±0.10^{d}	1.62 ±0.39^{cd}	1.66 ±0.08^{cd}	1.71 ±0.24^{d}
TPC (mg GAE/g)	0.26 ±0.11^{a}	0.33 ±0.03^{ab}	0.43 ±0.18^{abc}	0.35 ±0.07^{ab}	0.59 ±0.12^{bc}	0.68 ±0.05^{c}	0.65 ±0.06^{c}	0.67 ±0.12^{c}	0.69 ±0.04^{c}
DPPH (%)	70.97 ±0.62^{b}	74.61 ±0.71^{d}	82.04 ±0.57^{f}	68.34 ±0.57^{a}	69.18 ±0.57^{a}	77.25 ±0.46^{e}	67.93 ±0.57^{a}	73.04 ±0.38^{c}	75.85 ±0.35^{de}
ABTs (%)	56.71 ±0.52^{a}	62.40 ±0.94^{b}	87.14 ±0.56^{e}	80.61 ±0.80^{c}	81.73 ±0.14^{c}	88.68 ±0.62^{e}	79.36 ±0.80^{c}	84.46 ±0.79^{d}	87.28 ±0.75^{e}

Note: Table shows mean values ± standard deviation.

^{a,b} - Different index letters in the same row indicate that the values are significantly different ($P \leq 0.05$).

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3.3. Modeling of Drying Behavior

To model moisture ratios experimentally for each drying treatment, nonlinear regression was calculated for 22 thin-layer models. The results of the five best models, which have an acceptable fit to the drying behavior of lemon slices, were selected; with the estimated values and statistical data represented in Table 3. The goodness of fit of the models tested to experimental data was based on the highest adjusted R^2 values and the lowest χ^2 and RMSE values. However, the Fernando and Amarasinghe model was found to be the best model to describe the drying kinetics of lemon slices. This model provides the highest R^2 ($R^2 \geq 0.9995$), the lowest χ^2 ($\chi^2 \leq 0.000039$), and the lowest RMSE ($RMSE \leq 0.005987$).

It can therefore be assumed that this model provides a good representation of the drying kinetics of lemon slices in the MD, CD, and CMD treatments. Better prediction of the experimental drying data by Fernando and Amarasinghe (2016) model has also been reported by Fernando and Amarasinghe (2016) to describe the drying kinetics of coconut coir pith using hot air, Guemouni et al. (2022) to model the thin-layer drying kinetics of tomato slices in microwave treatment, and Fordjour, Sarpong, Owusu-Kwarteng, and Boateng (2024) to mathematically model the thin-layer drying kinetics of coconut meat slices.

Table 3. Estimated values of coefficients and statistical analyses for each model of lemon drying kinetics.

Models	**Drying conditions**		**Model constants**			**Statistical parameters**		
						R^2	**χ^2**	**RMSE**
Fernando and Amarasinghe (2016)	CD	50°C	$a = -0.001$	$b = 0.000$	$c = 0.002$	0.9994	5.20×10^{-5}	6.97×10^{-3}
		60°C	$a = -0.001$	$b = 0.000$	$c = 0.002$	0.9992	6.90×10^{-5}	7.98×10^{-3}
		70°C	$a = -0.003$	$b = 0.000$	$c = 0.002$	0.9962	3.62×10^{-4}	1.79×10^{-2}
	MD	180 W	$a = -0.018$	$b = 0.000$	$c = 0.017$	0.9923	6.21×10^{-4}	2.47×10^{-2}
		540 W	$a = -0.033$	$b = -0.000$	$c = 0.135$	0.9994	4.50×10^{-5}	6.53×10^{-3}
		900 W	$a = -0.038$	$b = -0.001$	$c = 0.137$	0.9995	3.90×10^{-5}	5.99×10^{-3}
	CMD	540 W/50°C	$a = -0.078$	$b = 0.001$	$c = 0.036$	0.9978	1.95×10^{-4}	1.35×10^{-2}
		540 W/60°C	$a = -0.121$	$b = 0.004$	$c = 0.020$	0.9981	1.84×10^{-4}	1.31×10^{-2}
		540 W/70°C	$a = -0.129$	$b = 0.004$	$c = 0.005$	0.9951	5.00×10^{-4}	2.13×10^{-2}
Logistics	MD	180 W	$a = 5.379$	$b = 6.688$	$k = 0.041$	0.9933	5.37×10^{-4}	2.30×10^{-2}
		540 W	$a= 3.23\times10^{5}$	$b= 3.11\times10^{5}$	$k = 0.125$	0.9955	3.12×10^{-4}	1.72×10^{-2}
		900 W	$a = 2.132$	$b = 3.030$	$k = 0.186$	0.9936	5.27×10^{-4}	2.21×10^{-2}
	CMD	540 W/50°C	$a = 0.776$	$b = 1.722$	$k = 0.198$	0.9942	5.29×10^{-4}	2.23×10^{-2}
		540 W/60°C	$a = 0.468$	$b = 1.442$	$k = 0.316$	0.9982	1.81×10^{-4}	1.29×10^{-2}
		540 W/70°C	$a = 0.290$	$b = 1.201$	$k = 0.336$	0.9894	1.09×10^{-3}	3.15×10^{-2}
Logarithmic	MD	180 W	$a = 1.086$	$c = -0.040$	$k = 0.034$	0.9944	4.49×10^{-4}	2.10×10^{-2}
		540 W	$a = 0.968$	$c = -0.015$	$k = 0.119$	0.9959	2.81×10^{-4}	1.63×10^{-2}
		900 W	$a = 1.060$	$c = -0.093$	$k = 0.123$	0.9978	1.80×10^{-4}	1.29×10^{-2}
	CMD	540 W/50°C	$a = 1.120$	$c = -0.118$	$k = 0.105$	0.9974	2.39×10^{-4}	1.50×10^{-2}
		540 W/60°C	$a = 1.129$	$c = -0.082$	$k = 0.161$	0.9942	5.80×10^{-4}	2.32×10^{-2}
		540 W/70°C	$a = 1.229$	$c = -0.233$	$k = 0.116$	0.9919	8.30×10^{-4}	2.75×10^{-2}
Parabolic	CD	50°C	$a = 0.919$	$b = -0.001$	$c = 0.000$	0.9925	6.25×10^{-4}	2.42×10^{-2}
		60°C	$a = 0.896$	$b = -0.002$	$c = 0.000$	0.9861	1.14×10^{-3}	3.24×10^{-2}
		70°C	$a = 0.926$	$b = -0.003$	$c = 0.000$	0.9909	8.76×10^{-4}	2.78×10^{-2}
	CMD	540 W/50°C	$a = 0.957$	$b = -0.089$	$c = 0.002$	0.9964	3.29×10^{-4}	1.76×10^{-2}
		540 W/60°C	$a = 0.984$	$b = -0.126$	$c = 0.004$	0.9964	3.56×10^{-4}	1.81×10^{-2}
		540 W/70°C	$a = 0.977$	$b = -0.121$	$c = 0.004$	0.9958	4.33×10^{-4}	1.99×10^{-2}
Wang and Singh (1978)	CD	50°C	$a = -0.002$	$b = 0.000$		0.9821	1.45×10^{-3}	3.72×10^{-2}
		60°C	$a = -0.002$	$b = 0.000$		0.9683	2.51×10^{-3}	4.88×10^{-2}
		70°C	$a = -0.004$	$b = 0.000$		0.9825	1.61×10^{-3}	3.85×10^{-2}
	CMD	540 W/50°C	$a = -0.096$	$b = 0.002$		0.9937	5.56×10^{-4}	2.31×10^{-2}
		540 W/60°C	$a = -0.129$	$b = 0.004$		0.9961	3.78×10^{-4}	1.90×10^{-2}
		540 W/70°C	$a = -0.127$	$b = 0.004$		0.9951	4.88×10^{-4}	2.14×10^{-2}

Note: CD: Convective drying, MD: microwave drying, CMD: combined microwave Convective drying.
R^2, coefficient of determination; RMSE, root mean square error.

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3.4. Effective Moisture Diffusivity

The effective moisture diffusivity (D_{eff}) of lemon slices under various drying methods was estimated using the second Fick's law for unsteady-state diffusion. As shown in Table 2, D_{eff} ranged from 0.95×10^{-10} to 2.12×10^{-10} m^2/s for CD, from 9.66×10^{-10} to 48.7×10^{-10} m^2/s for MD, and from 57.42×10^{-10} to 69.13×10^{-10} m^2/s for CMD.

These values are consistent with those reported in the literature for food materials, falling within the typical range of 10^{-12} to 10^{-8} m^2/s for agricultural products, such as those cited by Darvishi et al. (2014) for lemon slices, Wang et al. (2014) for apple pomace, and Pinheiro and Castro (2023) for banana slices. D_{eff} was found to increase with both microwave power and air temperature, although the influence of microwave power was more pronounced, corroborating earlier findings (Darvishi et al., 2014). At high microwave power, rapid bipolar molecule rotation generates heat, enhancing mass transfer and increasing D_{eff} (Yilmaz et al., 2021).

CMD significantly enhanced D_{eff}, with values improving by 38-fold at 540W/50°C and 46-fold at 540W/70°C compared to CD. This improvement is attributed to the synergistic interaction of microwave-induced internal heating and convective surface evaporation, a phenomenon also reported in earlier studies (Darvishi et al., 2014; Quan et al., 2023). In MD, the absorption of microwave energy by water molecules promotes rapid molecular oscillation and friction, generating internal heat that enhances moisture migration.

ANOVA results confirmed significant differences in D_{eff} between the drying methods ($P < 0.05$). While D_{eff} varied significantly with drying conditions in MD and CMD, no significant effect ($P > 0.05$) was observed for temperature variation in CD. Based on D_{eff} values, the drying methods were ranked: CMD 540W/70°C > CMD 540W/60°C > CMD 540W/50°C > MD 900W > MD 540W > MD 180W > CD 70°C > CD 60°C > CD 50°C.

3.5. Energy Consumption

As shown in Table 2, the energy performance of the different drying methods was assessed using Specific Energy Consumption Efficiency (SEC_e) and Energy Efficiency (EE). Higher microwave power levels and elevated air temperatures led to lower SEC_e and higher EE, indicating improved EE. There was a wide variation in SEC_e values across the drying methods, with CD being the most energy-intensive method of drying, having SEC_e values ranging from 6.06×10^7 to 11.77×10^7 MJ/kg. By contrast, MD was more efficient and had SEC_e values from 0.11×10^7 to 0.48×10^7 MJ/kg; the lowest SECe was 900 W (0.11×10^7 MJ/kg). For CMD, the SEC_e values of approximately 0.23×10^7 to 0.34×10^7 MJ/kg were about 90% lower compared to that obtained for CD and were second to MD at 900 W regarding energy consumption.

It was observed that EE was inversely related to SEC_e, a confirmation of trends reported in earlier research works (Kaveh et al., 2021; Maftoonazad, Dehghani, & Ramaswamy, 2022; Wang et al., 2014). At the same conditions, the lowest values of EE were recorded by CD, in the range $0.19 \times 10^{-2}\%$ to $0.37 \times 10^{-2}\%$, while the highest values were recorded by MD within the range $4.69 \times 10^{-2}\%$ to $19.96 \times 10^{-2}\%$, with a peak at 900 W. CMD, however, presented intermediate values of EE between $6.73 \times 10^{-2}\%$ and $9.76 \times 10^{-2}\%$, showing a balance between energy saving and drying performance.

The inverse SECe and EE relationship can be attributed to two main factors: the enhanced moisture gradients that occur at higher air temperatures, which promote moisture diffusion and lower drying time, as well as EE improvements (Jahanbakhshi, Yeganeh, & Momeny, 2020). In a similar manner, high microwave radiation increases D_{eff}, which leads to greater drying due to the structural change in plant tissue (Torki-Harchegani et al., 2016).

The drying techniques sorted in order of energy efficiency are: MD 900W > CMD 540W/70°C > CMD 540W/60°C > CMD 540W/50°C > MD 540W > MD 180W > CD 70°C > CD 60°C > CD 50°C. These results confirm that MD at 900W is the most energy efficient drying method. However, CMD is still a very viable choice since it offers an excellent compromise between energy use efficiency and product quality. CD used more energy than all other drying methods, with less efficiency that scored the lowest on the ranking scale.

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3.6. Effect of Drying on Bioactive Compounds

Table 2 illustrates the influence of CD, MD, and CMD on TFC and TPC retention in dried lemon slices. The results demonstrate that drying conditions significantly influenced bioactive compound preservation ($P < 0.05$), in which the CMD and MD were most effective in maintaining the TFC and TPC levels.

The results showed that maximal retention was observed in CMD at 540W/70°C, with TFC reaching 1.71 mg QE/g DW and TPC 0.69 mg GAE/g DW. On the contrary, maximal loss was recorded under CD at 50°C, with the TFC reduced to 0.64 mg QE/g DW and TPC to 0.26 mg GAE/g DW. These results are in agreement with previous studies by Guemouni et al. (2022) and Keser et al. (2020) in which higher drying temperatures promote the retention of flavonoids and phenolics due to increased moisture removal and restricted oxidation.

This results in better retention in CMD and MD due to the rapid elimination of moisture that prevents enzymatic breakdown and oxidation. High temperatures promote Maillard reactions, which increase antioxidant activity (Ghanem et al., 2015). Microwave drying provides enhanced extraction of phenolic compounds due to the destruction of cell walls of plants through heat and vapor pressure, therefore improving bioavailability of bound phenolics (Dahmoune et al., 2015).

Drying time is also very important, given the increased degradation of TFC and TPC with longer exposure. CD at 50°C resulted in a 62% loss of TFC, whereas MD at 180W resulted in a 49% reduction. In this way, it is possible to point out that drying time affects bioactive retention more significantly than temperature, since longer exposure causes plant structures to collapse, making phenolics less extractable (Ghanem et al., 2015; Lee, Chin, & Chung, 2015).

CMD 540W/70°C and MD 900W were the most effective methods for retaining both phenolics and flavonoids. Both methods enable high-speed drying and reduce oxidative degradation of the compounds, making them quite promising for industrial applications. In contrast, CD 50°C resulted in the highest losses, confirming that longer drying times accelerate the degradation of nutritional compounds.

3.7. Effect of Drying on Antioxidant Activity

The antioxidant efficacy of lemon powder produced by CD, MD, and CMD drying was evaluated using DPPH and ABTS assays (Table 2). The antioxidant retention was significantly affected by drying ($p < 0.05$), with differences relying significantly on microwave power and drying temperature.

In CD, inhibition by DPPH was raised from 70.97% at 50°C to 82.04% at 70°C, while levels of ABTS were raised from 56.71% to 87.14%. This enhancement is attributed to decreased drying time at higher temperatures, which limits oxidative and enzymatic breakdown of phenolic compounds and ascorbic acid. Moderate heat treatment also improves the liberation of bound phenolics from cell walls, thereby increasing extractable antioxidant content (Kumar et al., 2022; Papoutsis et al., 2017; Zhao et al., 2025). Excessive heating, however, may lead to oxidative polymerization and some loss of antioxidant potential (M'hiri et al., 2018).

For MD, increasing power from 180 W to 900 W amplified inhibition of DPPH from 68.34% to 77.25%, and ABTS activity from 80.61% to 88.68%. Internal heating, which is rapid at higher power, hastens drying out of moisture and inhibits oxidative damage, preserving heat-sensitive bioactive compounds (Calin-Sanchez et al., 2020). Microwaves' volumetric energy transfer destabilizes cellular structures, enhancing phenolic extraction. At high intensities, few Maillard reactions can occur, resulting in melanoidins with high radical scavenging activity that increase antioxidant activity further (Calin-Sanchez et al., 2020; Santos et al., 2025).

The CMD process indicated intermediate but steady antioxidant retention with DPPH inhibition ranging from 67.93% to 75.85% and ABTS ranging from 79.36% to 87.28%. Synergy between microwave volumetric heating and convective airflow ensures faster and more efficient drying, reducing oxidative stress on bioactives. Similar CMD improvements in citrus and pomelo drying have been reported (Quan et al., 2023; Yildiz & İzli, 2019).

According to results in Table 2, optimum retention of antioxidants was under MD at 900 W and CD at 70°C. These conditions demonstrate that rapid evaporation of moisture coupled with moderate heating is effective in

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stabilizing heat-labile antioxidant compounds through inhibition of oxidative as well as enzymatic breakdown. The trends noted are consistent with previous findings (Calin-Sanchez et al., 2020; Quan et al., 2023; Yildiz & İzli, 2019), which confirm that both drying kinetics and energy intensity are key determinants in maintaining the biochemical stability of citrus products.

3.8. Color Analysis

The color of dried lemon slices is a critical quality parameter and among the first attributes perceived by consumers. An ideal color closely resembling the fresh sample indicates minimal degradation during drying. Color parameters L* (lightness), a* (red-green), b* (yellow-blue), and total color difference (ΔE) for fresh and dried lemon slices under different drying conditions are presented in Table 4.

All drying methods resulted in a decrease in L* and b* values and an increase in a* compared to fresh slices. These changes are strongly associated with browning: lower L* values indicate darkening, reduced b* reflects loss of yellowness, and a shift in a* from negative to positive denotes green loss and a redder appearance.

The degradation of carotenoid pigments and non-enzymatic Maillard browning reactions are primary causes of color loss (Calin-Sanchez et al., 2020). Extended drying times in CD and high microwave temperatures further contribute to discoloration. Kesbi et al. (2016) reported that excessive microwave power negatively impacted color in dried lemon, apple, and spinach.

ΔE is a widely used indicator of overall color change. M'hiri et al. (2018) categorized ΔE values from imperceptible (0 - 0.5) to great color difference (6.0 -12.0). In this study, CMD at 540W/50°C (ΔE = 7.16 ± 1.45) and MD at 540W (ΔE = 7.39 ± 1.8) showed the best color retention, while CD at 70°C exhibited the highest ΔE (16.77 ± 0.67), indicating the most discoloration.

These findings align with the conclusions of Alibas and Yilmaz (2022) who reported minimal color loss in orange slices dried by microwave. They showed that the microwave drying technique is the most effective method in terms of color preservation. Microwave energy at moderate power levels drives internal moisture toward the surface, allowing rapid evaporation while limiting surface overheating and browning (Darvishi et al., 2014).

Wang et al. (2014) and Kesbi et al. (2016) also confirmed the effectiveness of microwave drying in preserving visual and sensory quality. Best color retention was achieved with CMD at 540W/50°C and MD at 540W, while CD at 70°C caused the most degradation. These results affirm that moderate power MD is highly suitable for producing high-quality, visually appealing dried lemon slices.

Table 4. The color parameters, L*, a*, b* and ΔE values of fresh and dried lemon slices at different drying methods (Mean of six readings).

		L*	**a***	**b***	**ΔE**
Fresh Lemon	-	53.87 ± 1.04^{d}	-1.87 ± 0.32^{a}	23.74 ± 0.86^{def}	-
CD	*50 °C*	46.65 ± 1.8^{bc}	1.48 ± 0.33^{cd}	28.11 ± 0.98^{g}	9.04 ± 1.66^{ab}
	60°C	43.02 ± 1.24^{ab}	0.73 ± 0.02^{b}	26.51 ± 1.06^{fg}	11.64 ± 0.61^{abc}
	70°C	40.74 ± 0.84^{a}	2.02 ± 0.33^{d}	14.78 ± 1.57^{a}	16.77 ± 0.67^{c}
MD	*180 W*	45.81 ± 2.04^{bc}	0.54 ± 0.15^{b}	25.72 ± 0.38^{efg}	8.58 ± 1.04^{a}
	540 W	47.32 ± 1.27^{bc}	0.85 ± 0.13^{bc}	21.61 ± 1.36^{cde}	7.39 ± 1.8^{a}
	900 W	42.67 ± 0.29^{ab}	1.81 ± 0.25^{d}	16.19 ± 0.94^{ab}	14.26 ± 1.23^{bc}
CMD	*540W/50°C*	49.33 ± 2.81^{cd}	0.67 ± 0.12^{b}	19.62 ± 2.15^{bcd}	7.16 ± 1.45^{a}
	540W/60°C	47.15 ± 2.26^{bc}	0.62 ± 0.14^{b}	18.07 ± 1.92^{abc}	9.14 ± 3.61^{ab}
	540W/70°C	46.04 ± 1.07^{bc}	0.75 ± 0.2^{b}	17.33 ± 2.14^{ab}	10.67 ± 1.8^{ab}

Note: CD: Convective drying, MD: microwave drying, CMD: combined microwave Convective drying.
^{a,b} Means with different superscripts within the column are significantly different ($p < 0.05$).

4. CONCLUSIONS

The present work compared the efficiency of three lemon slice drying methods: CD, MD, and CMD. The comparison was based on various aspects such as drying time, drying kinetics, effective diffusivity, energy

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consumption, and bioactive compounds retention, antioxidant activity, and color attributes. The modeling of drying kinetics revealed that the Fernando and Amarasinghe (2016) model best represented these processes.

The results indicated that CD conducted at 50°C, 60°C, and 70°C was significantly slower (720 to 1350 minutes) when compared to MD and CMD. Therefore, the results for the efficiency of drying rate and effective diffusivity were improved with power and temperature (i.e., CMD at 540W/70°C achieved 0.64 kg H_2O/kg dm.min and 69.13×10^{-10} m^2/s, respectively). In addition, CMD and MD exhibited much lower specific energy consumption (SEC_e) (less than 0.11 MJ × 10^7/kg H_2O) whilst increasing energy efficiency, where the MD process conducted at 900W achieved the highest efficiency (19.96×10^{-2} %). Regarding overall quality, the CMD conducted at 540W/70°C had higher activity, with retention of phenolic compounds and improved antioxidant activity. The MD process itself is associated with efficiency in terms of energy, but CMD, or the combined process, showed a better compromise between drying rate, energy input, and retention of nutritional properties. This finding demonstrates that CMD is an effective alternative to optimize the drying process of lemon slices with energy economy and retention of biochemical and sensory properties.

Future research should be directed to the scale-up and industrial application of CMD technology, as well as its application to other fruits and vegetables in order to assess its versatility across different product matrices. All of these facets should explore further the influence of CMD design parameters on color intensity, functional quality, rehydration characteristics, and pigment content (e.g., carotenoids, flavanones). Such studies would lead to a further understanding of process–quality relationships and to the manipulation of drying parameters specific to food processing and for industrial purposes.

Funding: This study received no specific financial support.
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

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APPENDIX

Table A. Mathematical derivation and simplification of Fick's second law for the determination of effective moisture diffusivity (Deff).

Eq.No.	Expression	Description	Parameters
(A1)	$MR=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}e^{\left(-\frac{(2n+1)^2\pi^2}{4L^2}D_{eff}t\right)}$	Fick's second law for unsteady-state moisture diffusion in an infinite slab. Assumes uniform initial moisture, constant D_{eff}, negligible external mass transfer resistance, and symmetrical drying from both faces.	MR: moisture ratio; D_{eff}: effective moisture diffusivity (m^2 s^{-1}); t: drying time (s); L: half-thickness (m); n: integer index.
(A2)	$MR\approx\frac{8}{\pi^2}\exp\left[-\frac{\pi^2 D_{eff}t}{4L^2}\right]$	Simplified form obtained by retaining only the first term (n = 0) of the series in Eq. (A1). Valid for thin-layer drying, where higher-order terms decay rapidly.	Same as Eq. (A1); L: The half-thickness of the lemon slice, L = 0.0025 m (drying occurred on two faces).
(A3)	$\ln(MR)=\ln\left(\frac{8}{\pi^2}\right)-\left(\frac{\pi^2 D_{eff}}{4L^2}\right)t$	Taking the natural logarithm of Eq. (A2) yields a linear relationship between ln(MR) and t, allowing regression analysis to estimate D_{eff} from the slope of the line.	ln(MR): natural logarithm of moisture ratio; t: drying time (s).
(A4)	$Fo=D_{eff}\left(t/4L^2\right)$ $F_0=-0.101\ln(MR)-0.0213$	Empirical linear correlation between the Fourier number (Fo) and ln(MR), obtained by regression fitting of experimental data	Fo: Fourier number (dimensionless); MR: moisture ratio.
(A5)	$D_{eff}=Fo\frac{4L^2}{t}$	Final working equation used to calculate the effective moisture diffusivity, expressed in terms of the Fourier number and drying time.	D_{eff}: effective diffusivity (m^2 s^{-1}); L: half-thickness (m); t: drying time (s); Fo: Fourier number (dimensionless).

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