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ORIGINAL ARTICLE

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Drying Kinetics and Mathematical Modeling of Algerian Red-Hot Pepper (*Capsicum Annuum* L.) Utilizing Microwave Radiation

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ABSTRACT

Background: Drying is considered a good practice to preserve fruits and vegetables from spoilage and microbial growth. So, their use can be extended after the harvest periods. *Capsicum annuum* L. is a popular spice, but it cannot be stored in its fresh state due to its high moisture content. This is where the importance of microwave drying as a developed method lies.

Aims: This study focuses on the characteristics of drying kinetics of red-hot peppers using a microwave oven under various microwave powers to analyze drying parameters. Drying models help to better understand the drying behavior.

Methods: Different powers were used in the drying process. Moisture losses in the samples were recorded periodically to their equilibrium moisture. Drying parameters were calculated using mathematical equations. The experimental data were fitted to sixteen thin-layer models.

Results: The characteristics of drying kinetics were determined microwave drying time decreased notably from 80 to 24 s with the increasing power from 200 to 1200 W in two main stages a warming-up and a falling-rate phases. Drying rates (DR) increased progressively during the initial drying stage (0.1152 and 0.4012 $\mathrm{Kg_{Water}/(Kg_{dry\ matter}\ s)}$ for 200 and 1200 W, respectively) then decreased substantially during the final stage. A third-order polynomial relationship was found to correlate the effective moisture diffusivity with moisture content. The effective moisture diffusivity (D_{eff}) increased significantly with microwave power with the decrease in the moisture content (2.83 ($\times 10^{-8}$) ± 0.1834 and 12.9 ($\times 10^{-8}$) ± 0.2637 $\mathrm{m^2/s}$ for 200 and 1200 W. respectively). The calculated energy activation (E_a) was found 23.48 ± 0.987 $\mathrm{W/g}$. The least specific energy consumption (SEC_e) increased with increasing powers (1.55 ($\times 10^{+8}$) ± 0.01 and 2.76 ($\times 10^{+8}$) ± 0.0153 $\mathrm{MJ/kg}$ H_2O for 200 and 1200 W, respectively). Conversely to the energy efficiency values (EE) (14.55 ($\times 10^{-4}$) ± 0.0881 and 7.84 ($\times 10^{-4}$) ± 0.0078 % for 200 and 1200 W). The Hii model was found to be the best fit to describe microwave drying kinetics.

Conclusions: Microwave drying has several advantages, such as drying time reduction and less energy consumption, while achieving higher drying efficiency at a moderate power level. Therefore, this innovative process is recommended in industrial food processing.

Keywords: *Capsicum annuum* L.; Drying Kinetics; Mathematical Modeling; Diffusion; Activation Energy; Energy Consumption.

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1 INTRODUCTION

Understanding global population growth is crucial for planning future energy and food demands (United-Nations, 2019). The *Capsicum annuum* L., a vital species within the *Solanaceae* family (Tunde-Akintunde, 2010), is extensively cultivated worldwide for its pungent flavor, vibrant coloration, and considerable nutritional value (de Jesús Ornelas-Paz *et al.*, 2013). This plant serves as a significant ingredient in food preparation, as well as in medicinal and industrial applications. Moreover, it constitutes an excellent source of vitamins, dietary fiber, carbohydrates, minerals, and antioxidants with over 3,000 varieties consumed in both fresh or dried forms (Berke & Shieh, 2012; Getahun *et al.*, 2020). In Algeria, *Capsicum annuum* L. represents the most widely cultivated pepper species, contributing approximately 0.174

million tons global production which reached an estimated 36.1 million tons (FAOSTAT, 2022; MADR, 2020). The plant holds significant agricultural importance as a principal ingredient in traditional Algerian dishes such as *Zeffiti*, *Shelita*, and *Chakhchoukha* (Bedjaoui *et al.*, 2022).

Red-hot pepper is highly perishable following harvest due to its elevated initial moisture content (75 – 85 % w.b.) (Getahun *et al.*, 2020); approximately 50 % of Algerian agriculture products, including red-hot peppers, sustain post-harvest losses (MADR, 2020). Drying is an essential preservation process that extends shelf life by reducing moisture content, thereby inhibiting both microbial proliferation and chemical degradation (Çelen *et al.*, 2017). To ensure that dried products meet quality and nutritional standards,, it is essential to determine key moisture-transfer parameters—including drying rate, effective moisture diffusivity, and mass transfer coefficient— on the basis of the most appropriate drying model (Hnin *et al.*, 2021).

Dried *Capsicum annuum* L. is a valuable spice whose quality is primarily evaluated through its color, which is governed by carotenoid pigments subject to both varietal and processing factors (Deng *et al.*, 2018). Although more than 200 drying system types exist for agricultural products, and several drying processes have been developed over time, the selection of an appropriate method depends on the physicochemical characteristics of the product and prevailing socioeconomic conditions (Alibas, 2014). Conventional and industrial drying methods are associated with several significant drawbacks, including prolonged drying times, risk of contamination, substantial quality degradation, and high energy consumption (Ashtiani *et al.*, 2020; Sledz *et al.*, 2017). Consequently, post-harvest losses for fresh products are estimated to range from 40 to 60 % of total production—an economically untenable situation for the agri-food industry to improve the efficiency of drying systems and preserve the quality of dried products (Al-Harahsheh *et al.*, 2009; Darvishi *et al.*, 2014). In response, various pretreatment strategies and advanced drying techniques have been developed with the aim of reducing drying time and preserving the nutritional value of agricultural products throughout the drying process.

Microwave drying has emerged as an innovative and highly efficient technique for drying various high-moisture agricultural products, including red peppers, fruits, and medicinal herbs (Çelen *et al.*, 2017; Darvishi *et al.*, 2014; Darvishi *et al.*, 2016; Mouhoubi *et al.*, 2022; Tarafdar *et al.*, 2021). Compared to conventional drying methods, it offers numerous advantages, including a reduction in drying time of 25–90%, an increase in drying rate up to 8–9 times, and a decrease in energy consumption of 32–71% (Moses *et al.*, 2014). Previous studies have demonstrated that microwave power level, drying duration, and relative humidity are among the most influential factors governing both product quality and drying efficiency. The method also offers additional benefits in terms of process controllability, rapid start-up and shutdown, more compact equipment design, and precise regulation of drying parameters. Additionally, intermittent microwave applications have proven especially effective, as they reduce overheating and promote more uniform moisture distribution. These combined advantages render microwave drying a preferred technique in the food industry and a promising candidate for commercial-scale implementation (Tarafdar *et al.*, 2021).

Mathematical modeling of thin-layer drying is essential for optimizing drying conditions, predicting product behavior, designing efficient dryers, and minimizing experimental time and cost (Harish *et al.*, 2014). Empirical and semi-empirical models are widely employed in food drying research to predict moisture loss, heat transfer, microwave power effect, quality attributes, and to estimate effective moisture diffusivity (Onwude *et al.*, 2017). However, studies specifically addressing the modeling of microwave drying of *Capsicum annuum* L. remain limited (Darvishi *et al.*, 2014). The present study focuses on identifying the most physically appropriate drying model by comparing sixteen thin-layer drying models under strong microwave power conditions (up to 1,200 W) — parameters seldom studied for this product, and particularly for Algerian cultivars. The objective is to determine a model that not only achieves the best statistical fit, but also accurately reflects the dominant moisture transport mechanisms operative under microwave heating conditions.

Accordingly, the present study aimed to investigate the microwave drying kinetics of an Algerian red-hot pepper at various power levels by modeling drying behavior, estimating effective moisture diffusivity and activation energy, as well as evaluating energy efficiency alongside specific energy consumption. This work addresses a notable gap in the literature concerning microwave drying process of *Capsicum annuum* L., particularly within the Algerian context, and provides locally relevant data to support the optimization of drying processes within the Algerian agricultural sector.

2 MATERIAL AND METHODS

2.1 Plant Material and Sample Preparation

Fresh red-hot pepper variety (*Capsicum annuum* L.) fruits were harvested during the flowering period in October 2019 from an agricultural site in Boudouaou, Boumerdes (northeastern Algeria). Taxonomic identification was performed by a botanist based on distinctive morphological characteristics. Prior to experimental processing, the raw material was stored at 4°C ± 0.5$°C$ for a maximum of two days to maintain physiological integrity. Fruit selection was strictly constrained to specimens exhibiting uniform coloration and morphology, with no mechanical injuries or signs of microbial degradation.

Preceding the dehydration protocols, the peppers were washed, manually deseeded and destemmed, and subsequently sliced employing stainless-steel knifes. The physical dimensions of the resulting thin-layer specimens were determined via an analytical balance for mass (4.75 ± 0.63 g) and a digital Vernier caliper for spatial parameters, yielding a mean height of 5.59 ± 0.26 *cm*, a diameter of 3.22 ± 0.03 *cm* and a slice thickness of 3.7 ± 0.04 *mm*. Appropriate personal protective equipment, including powder-free gloves, was mandated throughout all handling stages to prevent contamination.

The initial moisture content of the fresh matrix was determined to be 80.68 ± 0.178 % on a wet-matter basis (w.m.) via convective oven drying (Memmert UFB500, Germany) in compliance with the standard AOAC method 934.06 (AOAC, 2000). Aliquots of approximately 5 g were thermally processed at 100 ± 1°*C* for six hours until a constant mass was achieved. All gravimetric measurements were executed in triplicate (n = 3), and the moisture content loss was quantified via employing Equation [1] (Li *et al.*, 2025).

$$M_{dm}(g_{Water}/g_{dry\ matter}) = \frac{W_i - W_f}{W_f} \qquad [1]$$

Where M_{dm} is the moisture content expressed on a dry matter basis (%),
"W_i" represents the initial sample mass (g),
"W_f" denotes the final dry sample mass.

2.2 Microwave Drying Experiments

Microwave drying of *Capsicum annuum* L. was performed utilizing an inverter microwave oven (LG, Model MH8265DIS, South Korea). To comprehensively evaluate the thin-layer drying kinetics across a wide operational spectrum, experiments were carried out at five power levels: 200, 400, 700, 1000, and 1200 *W*.

In alignment with established literature protocols designed to optimize electromagnetic field exposure and prevent sample overlapping within the resonant cavity, uniform 25 g of sample was distributed evenly in a single layer on the revolving turntable for each experimental run (Amarasinghe *et al.*, 2018; Van Man *et al.*, 2014). Moisture loss was monitored periodically at regular intervals of 5 seconds for 200 and 400 *W* regimens; 3 seconds for 700 and 1000 *W* regimens; and 2 seconds for the 1200 *W* regimen.

Mass differentials were recorded utilizing an external analytical balance (AND, GH-202, S/N 15103159, Japan) accurate to 0.001 g until asymptotic weight stability was reached. All drying treatments were performed in triplicate, (n = 3) and the resultant kinetic data were subjected to statistical mean calculations ($p < 0.05$).

2.2.1 Mathematical Modeling of Drying Kinetics

Mathematical modeling of thin-layer drying kinetics is highly critical for elucidating the underlying heat and mass transfer mechanisms governing moisture desorption profiles (Zhu *et al.*, 2024). Numerous empirical and semi-empirical mathematical formulations have been previously deployed to describe the moisture transport phenomena of pepper varieties (Arslan *et al.*, 2020; Ding *et al.*, 2025).

In the present study, sixteen distinct mathematical models were evaluated to determine their predictive accuracy. Model selection was validated based on standard non-linear regression statistical indices, specifically the coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ2). These selected models are also among the most frequently reported empirical and semi-empirical drying models in the literature, allowing for a meaningful comparison with existing scholarly datasets (Table 1).

The resulting drying curves characterize the variation in the moisture ratio *(MR)* as a function of drying time. The *MR*, which establishes the relationship between the moisture content at a specific temporal interval (M_t), the initial moisture content (M_0), and the equilibrium moisture content (M_e) expressed in identical gravimetric units

($g_{Water}/g_{dry\ matter}$) was determined using Equation [2] (Tepe & Tepe, 2020).

$$MR = \frac{M_t - M_e}{M_0 - M_e} = e^{-kt^n} \qquad [2]$$

Given that the magnitude of M_e can be disregarded and assumed to be zero for microwave drying (Darvishi *et al.*, 2016). Consequently, Equation [2] simplifies to the following equation:

$$MR = \frac{M_t}{M_0} \qquad [3]$$

2.2.2 Drying Rate

The drying rate (*DR*), describing the flux of moisture desorption per unit of time, was quantified according to Equation [4] (Li *et al.*, 2023).

$$DR = \frac{M_{t+dt} - M_t}{dt} \qquad [4]$$

Where;
DR is the drying rate ($g_{Water}/g_{dry\ matter}\ s$);
M_{t+dt} and M_t denote the mean moisture content ($g_{Water}/g_{dry\ matter}$), at $(t + dt)$ and t (s), respectively; and dt is the time difference (s).

Kinetic profiles and drying behavior were comprehensively evaluated by plotting the calculated drying rates against cumulative processing time (Li *et al.*, 2023).

2.2.3 Determination of Effective Moisture Diffusivity

The effective moisture diffusivity (D_{eff}) is a critical transport property governing internal mass transfer during the falling rate drying period (Motevali *et al.*, 2016). Assuming that red-hot pepper possesses a homogeneous infinite flat slab geometry for the *Capsicum annuum* L. slices, D_{eff} was estimated via a simplified form of Fick's second law of diffusion (Alibas, 2014). The relationship between moisture ratio (MR) and (D_{eff}) is defined by Equation [5] (Jongyingcharoen *et al.*, 2025).

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}e^{\left(-\frac{(2n+1)^2\pi^2}{4L^2}D_{eff}\right)} \qquad [5]$$

Where;

D_{eff} is the effective moisture diffusivity (m^2/s);

L is the half thickness of layer ($L = 0.00185m$) of red-hot pepper;

n is the positive integer;

t denotes the drying duration (s).

When the drying period extends over a considerable duration, equation [6] can be simplified as demonstrated (Kouhila *et al.*, 2020).

$$\ln(MR) = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \qquad [6]$$

Therefore, considering the numerical assessment involving the Fourier number $F_0 = \frac{D_{eff}t}{4L^2}$, equation **[6]** (Surendhar *et al.*, 2019) can be reformulated as equations [7] and [8] (Darvishi *et al.*, 2014).

$$\ln(MR) = \ln\frac{8}{\pi^2} - \pi^2 F_0 \qquad [7]$$

Resulting in:

$$F_0 = -0.101\ln(MR) - 0.0213 \qquad [7]$$

Ultimately, the localized effective moisture diffusivity was computed at each sampling interval via Equation [9] (Barforoosh *et al.*, 2024).

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

Table 1. Mathematical Thin Layer Drying Models from Various Authors Employed for the Study

Model name	Mathematical Equation	References
Page	$MR = e^{-kt^n}$	(Brahmi *et al.*, 2023)
Three Parameter	$MR = ae^{[-(kt)^n]}$	(Phoungchandang & Kongpim, 2012)
Midilli *et al.*	$MR = a\,e^{-kt^n} + bt$	(Brahmi *et al.*, 2023)
Hii *et al.*	$MR = a\,e^{(-kt^n)} + b\,e^{(-ct^n)}$	(Doymaz, 2014)
Kaleta I	$MR = a\,e^{(-kt^n)} + (1-a)\,e^{(-ct^n)}$	(Kaleta *et al.*, 2013)
Sripinyowanich and Noomhorm	$MR = e^{-kt^n} + bt + c$	(Ertekin & Firat, 2017)
Logistic	$MR = b/(1 + a\,e^{kt})$	(Brahmi *et al.*, 2023)
Sledz *et al.*	$MR = b\,e^{-kt}/(1 + a\,e^{ct})$	(Brahmi *et al.*, 2023)
Weibull distribution-I	$MR = a - b\,e^{-(kt^n)}$	(Brahmi *et al.*, 2023)
Haghi and Angiz-II	$MR = a + bt + ct^2 + dt^3$	(Ertekin & Firat, 2017)
Haghi and Angiz-III	$MR = a + bt/(1 + ct + dt^2)$	(Ertekin & Firat, 2017)
Modified drying	$MR = a + e^{-(kt^n)}$	(Hemis *et al.*, 2011)
Jena Das	$MR = a.e^{-kt+b\sqrt{t}} + c$	(Ertekin & Firat, 2017)
Balbay and Şahin	$MR = (1-a)\,e^{(-kt^n)} + b$	(Balbay & Şahin, 2012)
Hasibuan and Daud	$MR = 1 - at^n\,e^{-kt^n}$	(Ertekin & Firat, 2017)
Yun *et al.*	$MR = a + bt + ct^2/(1 + dt + kt^2)$	(Yun *et al.*, 2013)

** K is the drying constants (1/min); a, b, c, d are the coefficients of the equations; n is exponent; t is time (min).*

2.2.4 Estimation of Activation Energy

The effective moisture diffusivity (D_{eff}) is associated with the temperature (T) through the Arrhenius equation (Arslan *et al.*, 2020). Where energy activation (E_a) is determined by analyzing the slope of the Arrhenius plot, which relates $\ln(D_{eff})$ to $1/T$. For microwave drying, however, the E_a is not directly associated with air temperature. Instead, it is related to the sample weight and microwave output power, as indicated by equation [10] (Delfiya *et al.*, 2022). In this approach the measurement of the temperature inside the microwave is challenging. Consequently, the E_a was determined by analyzing the slope of the Arrhenius plot of $\ln(D_{eff})$ versus $1/T$, and its unit is represented in terms of (m/P).

$$D_{eff} = D_0 e^{\left(-\frac{E_a m}{P}\right)} \qquad [9]$$

Where;

D_{eff} is the effective diffusivity (m^2/s);

D_0 is the pre-exponential factor (m^2/s) in the microwave;

m is the mass of raw sample (g); and P is the power (W).

2.2.5 Energy Consumption and Process Efficiency

The energetic footprint and operational performance of the microwave drying protocol can be calculated through Equations [11] and [12], respectively (Zhang *et al.*, 2021).

$$\mathrm{SEC_e} = \frac{3600\mathrm{E}}{\mathrm{M_s}(\mathrm{X_i} - \mathrm{X_f})} \qquad [10]$$

Where:
$\mathrm{SEC_e}$ is specific electrical energy consumption ($MJ/$Kg of removed water);
E is total electrical energy consumption (KWh);
$\mathrm{X_i}$ and $\mathrm{X_f}$ are initial and final moisture contents (dm), respectively; and $\mathrm{M_s}$ is mass of dry solid matter (in Kg).

$$\mathrm{EE} = \mathrm{M_s}(\mathrm{X_i} - \mathrm{X_f})\,\frac{\Delta \mathrm{h_v}}{3600\mathrm{E}}\,100 \qquad [11]$$

Where:
EE is electrical energy (%);
$\Delta \mathrm{h_v}$ is evaporation enthalpy of water (2257 $KJ/$Kg, at 100°C).

2.3 Statistical Analysis

Nonlinear regression analyses for thin-layer drying model parameters were executed utilizing STATISTICA software (v.13.5.0.17). Model selection was based on statistical parameters: the highest determination coefficient ($\mathrm{R^2}$) value, the lowest values of chi-square (χ2) and root mean square error (RMSE) (Joo *et al.*, 2024). These values were calculated according to Equations [13], [14], and [15]:

$$\mathrm{R^2} = \frac{\sum_{i-1}^{N}(MR_i - \overline{MR}_{pre,i})^2 \sum_{i-1}^{N}(MR_i - \overline{MR}_{exp,i})^2}{\sum_{i-1}^{N}(MR_i - \overline{MR}_{pre,i})^2 \sum_{i-1}^{N}(MR_i - \overline{MR}_{exp,i})^2} \qquad [12]$$

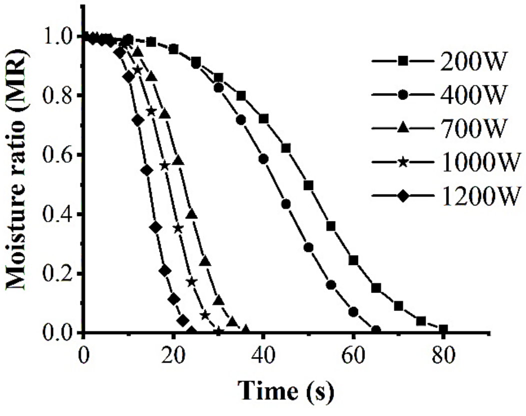

Figure 1. Moisture Ratio of Red-Hot Peppers over Time by Microwave (Source: Primary Research Data)

$$\chi 2 = \frac{\sum_{\mathrm{i-1}}^{\mathrm{N}}(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}})^2}{\mathrm{N} - \mathrm{z}} \qquad [13]$$

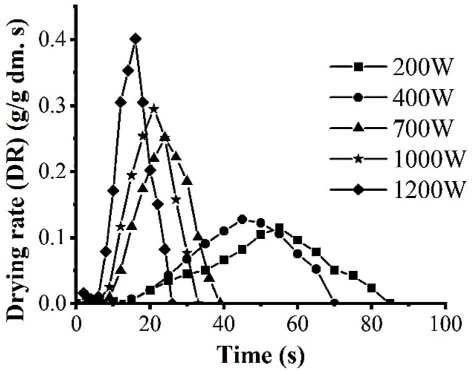

Figure 2. Variations of Drying Rate of Red-Hot Pepper Over Time by Microwave (Source: Primary Research Data)

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{\mathrm{i=1}}^{\mathrm{N}}(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}})^2}{\mathrm{N}}} \qquad [14]$$

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

All experimental trials were executed in triplicate, and data are reported as means ± standard deviation. One-way analysis of variance (ANOVA) followed by Tukey's post-hoc test ($p < 0.05$), was performed using STATISTICA software (v.13.5.0.17) to determine significant variations between means.

3 RESULTS

3.1 Microwave Drying Kinetics

3.1.1 Moisture Ratio Versus Drying Time

The microwave drying process is characterized by a progressive decrease in moisture content over time, until equilibrium is reached (Hidar *et al.*, 2020). Distinct kinetic profiles were recorded across power levels. As a result, through the concepts of heat and mass transfer, the drying time required to reach the lowest moisture content was 80 s (1.33 min), 65 s (1.08 min), 36 s (0.6 min), 30 s (0.5 min), and 24 s (0.4 min) at powers of 200, 400, 700, 1000, and 1200 W, respectively (Figure 1).

3.1.2 Drying Rate Versus Drying Time

The microwave drying of red-hot pepper under different powers follows two main phases (Figure. 2) based on the calculated drying rates from equation [4]: a first preheating period and a final falling rate period. In the current study, the initial drying rates of red-hot pepper were 0.1152, 0.1275, 0.2515, 0.2949, and 0.4012 $\mathrm{Kg_{Water}/(Kg_{dry\ matter}\ s)}$ at 200, 400, 700, 1000, and 1200 W, respectively, with less data points dispersion (Setyoningrum *et al.*, 2025). In the final stage, these values dropped to 0.0233, 0.0524, 0.0384, 0.0768, and 0.0823 $\mathrm{Kg_{Water}/(Kg_{dry\ matter}\ s)}$ (Figure 2).

3.1.3 Mathematical Modeling and Goodness-of-Fit

Experimental moisture ratio data points acquired during the microwave drying trials were fitted to empirical and semi-empirical models (Table 1). The goodness-of-fit of the models was evaluated statistically using the coefficient of determination (R^2), chi-square ($\chi 2$), and root mean square error (RMSE) indices (Table 2) (Kaveh & Amiri Chayjan, 2017).

Table 2. Modeling of Thin Layer of Red-Hot Pepper by Empirical and Semi-Empirical Models

Models	Drying conditions	Drying constants and coefficients					Statistical parameters		
	Power levels (W)	K	N	A	B	C	Adjusted R^2	X^2	RMSE
Three Parameters	**200**	0.01819	3.6111	0.9855			0.9993	7.74E-06	0.0025
	400	0.021244	3.8776	0.9928			0.9996	0.000031	0.0049
	700	0.040789	3.9464	0.9961			0.9999	0.000007	0.0023
	1000	0.048166	3.9189	0.9981			0.9998	9.38E-06	0.0026
	1200	0.062393	3.8433	1.0018			0.9994	0.0000055	0.0021
Midilli *et al.*	**200**	0.000001	3.5245	0.9903	-0.0003		0.9995	6.38E-07	0.0007
	400	4.63E-07	3.7668	0.9997	-0.0005		1.0000	3.91E-08	0.0002
	700	0.000004	3.9136	0.9978	-0.0002		0.9999	0.00016	0.0002
	1000	0.000008	3.877	1.0002	-0.0003		0.9999	0.00027	0.0003
	1200	0.000021	3.8813	1.0000	-0.0003		0.9995	0.00038	0.0004
Hii *et al.*	**200**	4.54E-07	3.6438	0.9817	0.0183	0.1355	0.9994	0.00001	0.0032
	400	0.000001	3.679	1.0199	-0.0239	-1.03E-07	1.0000	3.17E-13	4.52E-07
	700	0.000004	3.8731	1.0241	-0.0269	0.000001	0.9999	3.03E-10	0.00001
	1000	0.000008	3.8764	0.9994	-0.0005	-0.000006	0.9999	8.77E-10	0.00002
	1200	0.000001	4.6593	0.5756	0.4195	0.000006	0.9999	0.000005	0.0018
Kaleta I	**200**	0.000004	3.9842	0.0634		1.09E-07	0.9998	0.000019	0.0039
	400	0.000001	3.5847	1.1282		2.25E-07	0.9999	0.000021	0.0038
	700	0.000005	3.8251	1.088		0.000002	0.9999	0.00001	0.0028
	1000	0.000008	3.8617	1.0008		-0.000005	0.9999	1.81E-06	0.0011
	1200	0.000008	4.5117	0.4071		0.000002	0.9998	0.000063	0.0066
Sripinyowanich and Noomhorm	**200**	0.000001	3.4928		-0.0002	-0.0095	0.9994	5.69E-16	2.09E-08
	400	4.62E-07	3.7675		-0.0005	-0.0006	1.0000	2.1E-18	1.23E-09
	700	0.000004	3.9085		-0.0001	-0.0026	0.9999	7.66E-20	2.30E-10
	1000	0.000008	3.8803		-0.0003	-0.0001	0.9999	4.33E-19	5.25E-10
	1200	0.000021	3.8845		0.0004	-0.0005	0.9995	4.65E-16	1.8E-08
Weibull distribution-I	**200**	8E-07	3.4928	-0.021	-1.0087		0.9994	1.26E-19	3.11E-10
	400	6.9E-07	3.6604	-0.0432	-1.0393		1.0000	7.94E-31	7.53E-16
	700	0.000004	3.8883	-0.0091	-1.0061		0.9999	3.94E-20	1.65E-10
	1000	0.00001	3.8402	-0.013	-1.012		0.9999	4.69E-23	5.46E-12
	1200	0.000021	3.8943	0.0075	-0.9936		0.9995	6.49E-21	6.7E-11
Modified drying	**200**	0.000001	3.539	-0.0139			0.9994	8.12E-20	2.59E-10
	400	3.5E-07	3.8532	-0.0093			0.9997	6.16E-20	2.2E-10
	700	0.000003	3.9266	-0.0044			0.9999	6.38E-21	7E-11
	1000	0.000007	3.9133	-0.0032			0.9998	1.84E-19	3.66E-10
	1200	0.000023	3.8517	0.0026			0.9994	2.02E-16	1.25E-08
Jena Das	**200**	0.1702		-0.000001	3.0813	0.9883	0.9993	2.35E-18	1.34E-09
	400	0.219		-2.46E-07	3.6515	0.9952	1.0000	6.47E-25	6.8E-13
	700	0.4564		-9.28E-08	5.4348	0.9967	0.9999	6.53E-22	2.13E-11
	1000	0.5308		-1.14E-07	5.8247	0.9989	0.9999	1.14E-19	2.69E-10
	1200	0.6737		-1.53E-07	6.4997	1.0018	0.9990	6.18E-17	6.54E-09
Balbay and Şahin	**200**	0.000001	3.4928	-0.0087	-0.021		0.9994	3.99E-20	1.75E-10
	400	0.000001	3.6604	-0.0393	-0.0432		1.0000	4.58E-22	1.81E-11
	700	0.000004	3.8883	-0.0061	-0.0091		0.9999	1.98E-22	1.17E-11
	1000	0.000009	3.8402	-0.012	-0.0127		0.9999	9.94E-21	7.95E-11
	1200	0.000021	3.8943	-0.0064	-0.0075		0.9995	1.72E-17	3.46E-09
Hasibuan and Daud	**200**	0.000001	3.2839	0.000001			0.9992	0.00015	0.0109
	400	0.000002	3.4841	-0.000001			0.9997	0.000122	0.0098
	700	0.000007	3.7954	-0.000002			0.9999	0.000031	0.0049
	1000	0.000011	3.8219	-0.000002			0.9998	0.000015	0.0033
	1200	0.001594	2.598	-0.0016			0.9997	0.000044	0.0058

Source: primary research data

3.1.4 Effective Moisture Diffusivity

The Effective moisture diffusivity (D_{eff}) as a function of moisture content at powers of 200, 400, 700, 1000, and 1200 W is displayed in Figure 3. The D_{eff} values ranged from (2.83 × 10^{-8} ± 0.1834) to (12.9 × 10^{-8} ± 0.2637) $\mathrm{m^2/s}$ at the powers studied (Table 3). These values were within the range of (10^{-8} to 10^{-12} $\mathrm{m^2/s}$) for agricultural and food products under microwave drying (Kaveh *et al.*, 2018).

Table 3. Average Effective Diffusivity of Red-Hot Peppers at Different Microwave Power Levels

P (W)	D_{eff} ($\times 10^{-8}$) $\mathrm{m^2/s}$
200	2.83 ± 0.1834^a
400	3.69 ± 0.065^a
700	8.08 ± 0.5583^b
1000	9.75 ± 1.129^b
1200	12.9 ± 0.2637^c

*(Source: primary research data); * The table indicates the mean values and standard deviation; * The same index letters (a, b) indicate that the mean values are not significantly different at a 95% confidence level (p ≤ 0.05) for the same process.*

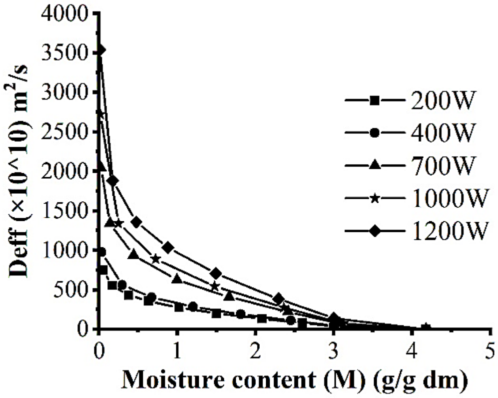

Figure 3. Variation in D_{eff} with Moisture Content by Microwave *(Source: primary research data)*

3.1.5 Activation Energy

The E_a for microwave drying was determined using equation [10], based on an Arrhenius plot and modeling approach. The resulting values E_a and K were determined to be 23.48 ± 0.987 $\mathrm{W/g}$ and 24.04 ± 1.611 $\mathrm{W/g}$, respectively.

3.1.6 Energy Consumption and Efficiency

The specific energy consumption (SEC_e) and energy efficiency (EE) of red-hot peppers at several microwave powers indicated an inverse proportional relationship (Table 4). powers indicated an inverse proportional relationship (Table 4).

Table 4. Specific Energy Consumption (SEC_e) and Energy Efficiency (EE) During the Drying of Red-Hot Pepper at Several Microwave Power Levels

P (W)	SEC_e ($\times 10^{+8}$ MJ/Kg H_2O)	EE ($\times 10^{-4}$ %)
200	1.55 ± 0.01^a	14.55 ± 0.0881^e
400	2.51 ± 0.01^c	9 ± 0.0315^c
700	2.43 ± 0.0252^b	8.96 ± 0.0103^d
1000	2.88 ± 0.0322^e	7.9 ± 0.0122^a
1200	2.76 ± 0.0153^d	7.84 ± 0.0078^b

*(Source: primary research data); * The table indicates the mean values and standard deviation; * The same index letters (a, b) indicate that the mean values are not significantly different at a 95% confidence level (p ≤ 0.05) for the same process.*

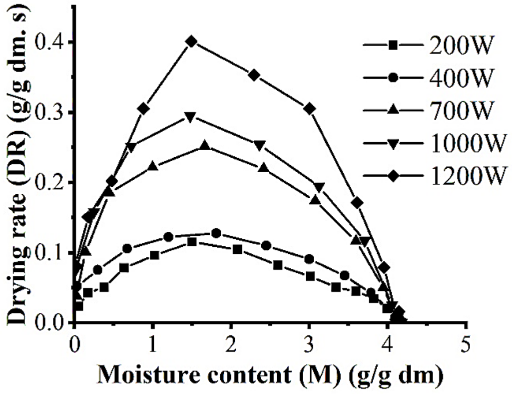

Figure 4. Variations of DR with Moisture Content of Red-Hot Pepper *(Source: primary research data)*

4 DISCUSSION

4.1 Microwave Drying Kinetics

The calculated initial moisture content was consistent with values reported in the literature for *Capsicum annuum* L., which typically range from 75 – 85 % (w.m.) (Getahun *et al.*, 2021). For instance, Deng *et al.* (2018); Getahun *et al.* (2021) observed initial moisture content of 74.40 ± 0.85 %, 79.60 ± 0.72 % respectively, while Fudholi *et al.* (2013) reported a value of 80.2 % (w.m.). Similarly, Anjaneyulu & Sharangi (2022) estimated water amounts of 76.87 and 80.68 % for sun drying, and 75.87 and 81.37 % for oven drying.

4.1.1 Moisture Ratio Versus Drying Time

The relationship between moisture ratio and drying time exhibited a non-linear profile, characterized by an initial rapid reduction in MR that subsequently decelerated as drying progressed (Figure 1). This kinetic pattern aligns with established observations in thin-layer drying literature. In the current study, governed by the principles of simultaneous heat and mass transfer, the drying duration required to reach the minimum moisture content was significantly reduced by factor of 3.33 when shifting from the lowest to the highest microwave power level. These findings in strong agreement with microwave drying characteristics documented by Arslan *et al.* (2020), Heydari *et al.* (2020), El-Mesery *et al.* (2025), and Onwude *et al.* (2016).

The drying curves converted to steeper when applying high microwave power due to the volumetric heating that increases the kinetic energy of internal water molecules, thereby accelerating their mobility and generating a substantial internal vapor pressure gradient. Consequently, this leads to a difference in moisture between the inside of the sample and its surface, rapidly driving moisture removal (Joardder & Karim, 2023; Mouhoubi *et al.*, 2019).

Handayani *et al.* (2022) noted that while conventional convective hot air faces significant thermal resistance when penetrating the dense outer cuticle of chili peppers, microwave energy directly penetrates the internal matrix heating the moisture via dipole rotation interactions. These authors reported a 99-fold reduction in drying time when comparing microwave drying at 110 W to open sun-drying under ambient temperatures ranging from 30 to 33 $°C$. In the current investigation, the drying time for red-hot pepper at 200 W was found 80 s, which is highly comparable to the results of the previous work.

4.1.2 Drying Rate Versus Drying Time

As illustrated in Figure 2, the total drying duration was strongly dependent on the applied power level. At lower power levels, prolonged drying times exceeding 60 $s$were observed, while at higher power levels (700 W and above), the drying duration decreased significantly to less than 36 s.

This initial phase of the process was characterized by an accelerated drying rate induced by effective microwave energy absorption through intense dipolar interactions among water molecules, which significantly reduces overall drying time (Motevali *et al.*, 2016). As previously noted, the significant internal vapor pressure gradient according to the characteristic volumetric heating of microwaves accelerates drying process.

As drying progressed, a falling-rate period commenced immediately after the drying rate reached its maximum across all power levels, persisting until the completion of the process. This decline in the drying rate is attributed by the reduction in energy absorption resulting from lower internal moisture, which decreases dipolar properties of the material and slows drying rate. This transition confirms that drying behavior is influenced by moisture diffusion and microwave energy absorption, which are strongly correlated with its moisture content (Abderrahim *et al.*, 2022). These results are in accordance with recent kinetics studies reported by Alqahtani & Fikry (2026), Araujo *et al.* (2024), and Zhang *et al.* (2023).

Overall, by applying powers from low to high levels drying rate increased, while the drying period decreased proportionally. The same impact of microwave powers on drying rate was also reported by Al-Harahsheh *et al.* (2009) and Darvishi *et al.* (2014).

4.1.3 Fitting of the Drying Models

The experimental data were fitted to sixteen thin-layer mathematical drying models. While all sixteen models demonstrated robust fit characteristics, ten models were statistically superior in describing the microwave drying kinetics of the red-hot pepper (Table 2). Specifically, The Three Parameter, Midilli, Hii, Kaleta-I, Sripinyowanich and Noomhorm, Weibull distribution-I, Modified drying, Jena Das, Balbay and Şahin, and Hasibuan and Daud models yielded the higher R^2 values (0.9990 – 1.0000), where $\chi 2$ (7.94×10^{-31}–3.8×10^{-4}) and RMSE (7.53×10^{-16}–0.0109) were notably the lower values.

Among these, the Hii model provided the most accurate prediction across all experimental conditions, demonstrating the highest R^2 (0.9994 to 1.0000) and the lowest values for $\chi 2$ (3.17×10^{-13} to 1.0×10^{-5}) and RMSE (4.52×10^{-7} to 0.0032). Consequently, the Hii model was selected as the most appropriate mathematical representation of the microwave drying behavior in this study. Its mathematical structure effectively captures the non-linear moisture removal and internal diffusion mechanisms, while its flexible exponential terms allow for an accurate representation of complex moisture migration and the progressive decrease in drying rates observed experimentally (Man *et al.*, 2022).

These mathematical models have been widely applied to describe the thin-layer drying kinetics of diverse agricultural commodities under varying processing methods. Within the context of pepper varieties, researchers have identified different optimal models; notably Darvishi *et al.* (2014), Krzykowski *et al.* (2024), Topuz (2022), and Yao *et al.* (2025). Beyond peppers, several distinct model preferences have been reported for other matrices by Sledz *et al.* (2017), Alvi *et al.* (2023), and Darvishi *et al.* (2013). These findings, including those of the present study, confirm that these models can effectively characterize the drying kinetics of various food products.

4.1.4 Drying Rate Versus Moisture Content

The drying rate behavior can be further explained by its relationship with moisture content (Figure 4), which standardizes the mass of moisture removed per unit time per unit of dry matter. Notably, a constant-rate drying period was absent across the entire range of applied microwave power levels. For the two lowest power levels, which standardizes the mass of occurred almost exclusively within the falling-rate phase apart, following a brief initial heating period required to reach the peak drying rate. This behavior is consistent with observations reported by Arslan *et al.*, 2020; Karimi *et al.*, 2021.

In the 700 to 1200 W power range, the drying rate increased substantially. This phenomenon is intensified by volumetric heating which causes rapid depletion of surface moisture and prevents the establishment of a stable constant-rate phase (Joardder & Karim, 2025). Furthermore, factors such as non-uniform heating and heterogeneous product structure may further limit the persistence of surface saturation, reinforcing the dominance of internal mass transfer mechanisms. Consequently, the system bypasses the constant-rate regime and proceeds directly to the falling-rate period.

A progressive increase in internal resistance to heat and mass transfer results in a falling-rate drying behavior (Hii *et al.*, 2023). Under these conditions, the migration rate of internal liquid moisture to the boundary layer becomes the limiting step, dictating that moisture must diffuse through the cellular matrix prior to phase change and subsequent evaporation at the surface.

At the maximum microwave power level, the peak drying rate was approximately 3.33 times higher than that observed at the lowest power level. This confirms that the drying rate is directly proportional to the applied power, whereas the total drying time is inversely proportional. These findings are in complete agreement with fundamental microwave drying studies on biological materials (Al-Harahsheh *et al.*, 2009; Araujo *et al.*, 2024; Arslan *et al.*, 2020).

4.1.5 Effective Moisture Diffusivity

Fick's second law of diffusion assumes that moisture transport operates along a unidirectional concentration gradient from the geometric core of the sample to its boundary layer (Zhang *et al.*, 2024). The D_{eff} characteristics within food matrices, includes molecular diffusion, vapor diffusion, capillary flow, and other potential mass transport mechanisms (Eminoğlu *et al.*, 2019).

The D_{eff} values of the red-hot pepper increased progressively, reaching maximum thresholds as the moisture content fell within the range of 0.04949 – 0.00833 $\mathrm{g_{Water}/g_{dry\ matter}}$ across the distinct power levels (Figure 4). The emergence of these diffusivity peaks coincided with a sharp increase in sample temperature during the final drying phase. This trend is attributable to the fact that falling moisture often correlates with an increase in vapor permeability, allowing the macro-porous cellular framework to remain open and interconnected (Lei *et al.*, 2020).

At the onset of processing, the temperature rises rapidly under microwave irradiation. Because the sample exhibits a high thermodynamic driving force when free water is abundant, rapid boiling generates significant internal vapor pressure within the pores. This pressure gradient can induce microstructural stress and localized pore enlargement, thereby increasing the macroscopic diffusivity (Joardder & Karim, 2023). Consequently, moisture is efficiently driven from the internal core toward the surface by a pressure-driven bulk flow mechanism (Horuz *et al.*, 2020).

Previous studies on microwave dried bamboo by Lv *et al.* (2019), microwave dried daylily by Ding ShengHua *et al.* (2012) and peppers drying by Darvishi *et al.* (2014) reported a decrease in moisture content with an increase in diffusivity and drew the same conclusions. Hence, liquid diffusion appears to be the primary mass transfer mechanism during the initial stage, resulting in reduced diffusivity. During the final stage, therefore, vapor diffusion became the predominant mechanism of mass transfer, leading to an increase in diffusivity.

Microwave penetration enhances diffusivity during the early stages, eliminating the constant-rate drying period constraining the process to the falling-rate domain. This behavior is consistent with previous literature confirming that microwave drying kinetics are governed by the interplay of volumetric heating efficiency and moisture diffusion (Abderrahim *et al.*, 2022; Darvishi *et al.*, 2013; Motevali *et al.*, 2016).

Variations in moisture diffusivity across different studies can be attributed to the impact of pepper variety, composition, and tissue properties (Darvishi *et al.*, 2013). Several studies reported values range from 7.204×10^{-13} to $1.08 \times 10^{-7}\ \mathrm{m^2/s}$ for various varieties of peppers, with D_{eff} rising with increasing microwave power (Darvishi *et al.*, 2014; Getahun *et al.*, 2021).

As presented in Table 3, D_{eff} increased significantly with increasing microwave power levels. Elevating the power level from 200 W to 1200 W led to an approximate 356% increase in diffusivity, which reduced the required drying time due to more efficient moisture removal at all moisture stages. This confirms that higher power levels correspond to higher D_{eff} because the increased electromagnetic energy absorption elevates both internal temperature and vapor pressure gradients, thereby accelerating liquid and vapor transport from the core to the surface (Wang *et al.*, 2026). Identical positive correlations between power level and moisture diffusivity have been reported for other agricultural commodities, including edamame (Islam *et al.*, 2019), potato (Azimi-Nejadian & Hoseini, 2019), *Moringa oleifera*

(Tarafdar *et al.*, 2021), dragon fruit (Khatun *et al.*, 2024), and coriander (Mouhoubi *et al.*, 2022).

Statistical analysis indicated no significant differences in the D_{eff} values between 200 and 400 W same as between 700 and 1000 W (Table 3). However, significant differences observed between larger power increments, specifically between 400 and 700 W and between 1000 and 1200 W. This indicates that a critical threshold of power increment is required to induce statistically meaningful modifications in the effective moisture diffusivity values.

4.1.6 Activation Energy

Although a standardized universal range for activation energy (E_a) does not exist for the microwave drying of fruits and vegetables, the values calculated in this study fall within the typical ranges reported in the literature. For instance, Darvishi *et al.* (2014) reported an E_a of $14.67\ \mathrm{W/g}$ for pepper, Turhan *et al.* (1997) reported $28.4\ \mathrm{W/g}$ for red bell pepper, Darvishi *et al.* (2016) calculated $17.96–21.38\ \mathrm{W/g}$ for kiwi, Abano (2016) obtained $8.58–17.48\ \mathrm{W/g}$ for mango, and Minaei *et al.* (2012) noted 16.675 and $24.222\ \mathrm{W/g}$ for sweet and sour pomegranates, respectively. Conversely, Mouhoubi *et al.* (2019) reported a higher value of $77.3\ \mathrm{W/g}$ for celery drying. These discrepancies in activation energy among various biological matrices are governed by variations in chemical composition, physical tissue structure, specific surface area, variety, maturity stage, and sample preparation protocols (Onwude *et al.*, 2016).

4.1.7 Energy Consumption and Efficiency

The microwave power levels and moisture content directly influenced the specific energy consumption (SEC_e) and energy efficiency (EE). The mean SEC_e required to evaporate one kilogram of water from the red-hot pepper ranged from $1.55 \times 10^8 \pm 0.01$ to $2.88 \times 10^8 \pm 0.0322\ \mathrm{MJ/Kg}$ across the studied power levels (Table 4).

An evaluation of the relationship between applied power and SEC_e revealed an overlapping trend across intermediate power levels, with the absolute minimum value observed at 200 W and the maximum value at 1000 W. This initial upward trend in SEC_e suggests that at intermediate-to-high power levels, the rate of total electromagnetic energy input exceeds the kinetic rate of moisture vaporization, particularly during the initial transient phase of drying. While lower power levels require longer processing times, they utilize a more balanced energy input relative to the instantaneous moisture content, thereby minimizing unnecessary energy expenditure. This behavior aligns with findings reported by Darvishi *et al.* (2014). Additionally, overheating at higher power levels, pepper thickness, more fibrous skin, higher structural mass, and often a higher initial moisture content than various other products, requires substantial energy to evaporate water from its cellular structure (Tóth *et al.*, 2025).

Several literature sources focusing on SEC_e values values relative to the mass of water removed per power increment have reported that energy consumption decreases with increasing power (Abbaspour-Gilandeh *et al.*, 2021; Mouhoubi *et al.*, 2019; Mouhoubi *et al.*, 2022; Tepe *et al.*, 2022). These authors attribute the decline to the abundance of free water at the onset of drying, which couples efficiently with the microwave field, followed by an energy drop as moisture is depleted. Consequently, the findings of the present study do not contradict existing literature, but rather reflect the integrated total energy balance of the entire process.

The EE values decreased from $14.55 \times 10^{-4} \pm 0.0881$ to $7.84 \times 10^{-4} \pm 0.0078$ % as the microwave power increased from 200 to 1200 W (Table 4). At lower power levels, energy efficiency was maximized due to more effective dielectric coupling between the product and the microwave field. As drying progressed and the moisture content decreased, the material absorbed less energy due to the reduced interactions between microwave and material (Arslan *et al.*, 2020; Fotiou and Goula, 2024). At higher power levels, a larger fraction of the emitted microwave energy is dissipated to the cavity walls and surroundings. Concurrently, the rate of useful energy absorbed by the product for water evaporation increases less rapidly than the total energy, further reduceding net energy efficiency (Ling *et al.*, 2025). This result aligns with the findings on lemon, ginger, and *Ficus carica Linn* leaves reported by Tepe *et al.* (2022), Wang *et al.* (2026), and Yilmaz *et al.* (2021) respectively.

Statistical analysis indicated significant differences among distinct power levels (Table 4). The highest SEC_e values and lowest EE values were associated with the highest power levels (1000 and 1200 W), whereas the lowest SEC_e value and the highest EE value corresponded to the lowest power (200 W).

It was observed that the drying time was reduced by a factor of 3.33; this was accompanied by a 1.86-fold increase in SEC_e and a corresponding 1.86-fold decrease in EE. Because the minimum SEC_e ($1.55 \times 10^8 \pm 0.01\ \mathrm{MJ/kg}\ H_2O$) and maximum efficiency ($14.55 \times 10^{-4} \pm 0.0881$ %) were both secured at 200 W, it can be concluded that 200 W represents the optimal power for red hot pepper drying within the scope of this study.

To ensure the statistical validity and reproducibility of the data, all experimental trials were performed in triplicate. The low standard deviations calculated for drying rate, effective moisture diffusivity, and energy indicate that the process is highly repeatable ($p < 0.05$). Experimental uncertainties originated primarily from sample weighing, temporal measurements, and microwave power regulation. The analytical balance (accuracy of 0.001 g) introduced minimal uncertainty in calculating moisture content and drying rate. Additionally, the results observed with increasing microwave power were consistent across repeated experiments, confirming that measurement uncertainties did not significantly impact the overall conclusions of this study.

5 CONCLUSIONS

The thin-layer microwave drying kinetics, energy efficiency, and specific energy consumption of red-hot pepper (*Capsicum annuum* L.) were comprehensively investigated under various processing conditions. The primary findings of this research are summarized below:

- During microwave drying, the largest proportion of total moisture was removed during the transient warming-up and early drying phases under controlled power conditions.
- The microwave drying of red-hot pepper proceeded via two distinct hydrodynamic stages: a warming-up phase and a falling-rate phase. The initial stage was characterized by an accelerated drying rate without the emergence of a constant-rate period. The falling-rate stage commenced immediately after the drying rates reached their peak, persisting until the target moisture content was achieved. Lower power levels exhibited prolonged drying regimes compared to higher power inputs.
- Among the sixteen mathematical models evaluated to fit the experimental data, ten models demonstrated satisfactory convergence. The Hii model exhibited the highest statistical superiority, yielding an optimal coefficient of determination (R^2=1.0000). The calculated activation energy (23.48 ± 0.987 W/g) confirms the efficiency of microwave irradiation in accelerating internal water migration.
- Energy assessment revealed overlapping specific energy consumption SEC_e trends across intermediate powers, while net energy efficiency EE decreased as power escalated from 200 W to 1200 W. Within this framework, the 200 W power level was identified as the optimal operational setting, yielding a maximum EE of 14.55 ± 0.0881% and a minimum SEC_e of 1.55 ± 0.01 MJ/kg H_2O.

In conclusion, these results demonstrate that a lower power level of 200 W can be strategically employed to achieve an energy-efficient drying process without compromising process effectiveness. These findings provide a scientifically validated foundation for optimizing industrial-scale microwave drying configurations for red-hot pepper production, expanding the current literature on the post-harvest processing of *Capsicum annuum* L. Future investigations will evaluate the impact of these optimized drying conditions on critical quality attributes of the resulting pepper powder, including color indices, water activity, microstructure, retention of bioactive compounds, and overall antioxidant activity.

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