

Drying holy basil using combined microwave and hot-air technology: An analysis of drying kinetics, energy efficiency, and color retention

Sumol Sae-heng Pisitsungkakarn¹⁾, Anatticha Chanthaphan¹⁾, Thanit Swasdisevi²⁾, Ponlakrit Kumklam³⁾ and Weera Sriariyakul^{*1)}

¹⁾Research Centre for Combustion Technology and Alternative Energy, College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Bangkok 10800, Thailand

²⁾School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand

³⁾Faculty of Science and Technology, Rajamangala University of Technology Phra Nakhon, Bangkok 10800, Thailand

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Abstract

Holy basil (*Ocimum tenuiflorum*) is a perishable herb with a high moisture content. Traditional hot-air drying methods result in longer drying times, higher energy use, and reduced quality. This study investigates combined hot-air and microwave drying to improve drying efficiency, reduce energy consumption, and maintain product color. A drying method was developed to evaluate the effects of hot air temperature (60, 70, and 80 °C) and microwave power level (300, 400, and 500 W) on drying kinetics, moisture diffusivity, color retention, and energy consumption. A mathematical transport model was developed in COMSOL Multiphysics to simulate the drying process. The model showed good agreement with experimental data. The results showed that microwave-hot air drying substantially accelerated moisture removal. Higher microwave power and hot-air temperature reduced drying time and specific energy consumption while increasing the effective moisture diffusivity. Combined hot-air and microwave drying resulted in a lower total color change. The highest effective moisture diffusion coefficient ($2.79 \times 10^{-11} \text{ m}^2/\text{s}$) and the lowest total specific energy consumption (529.91 MJ/kg_{water evaporated}) were obtained at a hot-air temperature of 80 °C and a microwave power of 300 W.

Keywords: Holy basil, Microwave-hot-air drying, Drying kinetics, Specific energy consumption, Color retention, Mathematical modeling

1. Introduction

Holy basil, known locally as “kraphao,” is a widely used herb in Thai cuisine and traditional medicine because of its aroma, antioxidant activity, and anti-inflammatory properties. However, its high moisture content makes it perishable; therefore, effective preservation methods are necessary to extend its shelf life and maintain its quality for off-season availability and export markets. Drying is a common preservation technique, but conventional hot-air (HA) drying often results in long processing times, high energy consumption, and quality deterioration due to prolonged thermal exposure [1].

To address these limitations, microwave (MW)-assisted drying has emerged as a promising alternative drying method. Microwave energy volumetrically penetrates the material and directly heats water molecules, thereby accelerating moisture removal. The combination of MW energy with HA drying can further enhance drying efficiency, improve energy utilization, and better preserve product color and bioactive compounds. Previous studies on the drying of fruits, vegetables, and herbs have confirmed that hybrid drying methods reduce drying time and energy consumption while improving quality retention compared with conventional methods [2].

In recent years, MW drying has gained popularity because MW energy can effectively penetrate materials and promote water evaporation without causing surface damage [3]. Higher MW power levels reduce drying time [4, 5]. However, prolonged exposure to MW drying may cause heat accumulation within the material, which can damage the product and affect its quality, as reported for chilies [6]. This concern has encouraged the development of combined MW and HA drying methods to reduce thermal damage. This approach lowers energy consumption while providing higher drying rates, more uniform moisture distribution, and better color retention, resulting in dried products with quality characteristics closer to those of fresh chilies [7-9].

Recent studies have investigated step-down MW power strategies to minimize thermal damage while maintaining drying efficiency. For instance, Nathakaranakule et al. [3] applied a step-down MW power strategy for durian chips and reported improved quality retention. Similarly, Neamtang et al. [2] employed a step-down industrial MW-HA belt dryer for mango drying. In the present study, constant MW power was used as a baseline reference.

Drying thin agricultural products can cause substantial heat build-up, which may damage surface quality before the products reach the desired final moisture content [10]. Therefore, effective drying strategies are needed to preserve product quality. Researchers often rely on trial-and-error approaches to optimize drying conditions, which may require considerable time and resources. Currently,

*Corresponding author.

Email address: weera.s@cit.kmutnb.ac.th

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mathematical models based on the finite element method (FEM) are developed and solved using COMSOL Multiphysics to simulate drying processes. This approach simulates heat and mass transfer to predict drying behavior and determine the moisture diffusion coefficient. The model results can be validated against experimental data to improve the prediction of drying conditions and enhance process efficiency [11, 12].

This study explores the drying kinetics, temperature profiles, effective moisture diffusivity, color retention, and specific energy consumption of basil leaves under various HA temperatures and MW power levels. A mathematical model based on heat and mass transfer principles was developed using COMSOL Multiphysics to simulate the drying process and validate the model against experimental data. This study aims to determine the optimal conditions for combined MW-HA drying to achieve rapid moisture removal, high energy efficiency, and satisfactory color retention. The novelty of this study lies in: (1) its first application of combined MW-HA drying to holy basil with COMSOL-based heat and mass transfer simulation, (2) quantitative reporting of specific energy consumption using primary energy conversion, and (3) identification of trade-offs among drying time, energy use, and color retention for basil leaves. This research provides an incremental contribution to the existing literature on MW-HA drying of leafy materials.

2. Materials and methods

2.1 Experimental set-up

A combined MW-HA dryer was designed and constructed. The dimensions of its drying chamber were 0.8 m (length) $\times$ 0.5 m (width) $\times$ 0.3 m (height). Sample loading density was approximately 0.5 kg/m² of belt area. Holy basil leaves were arranged in a single layer with approximately 2 cm spacing between individual leaves. The magnetrons were positioned above the conveyor belt, 15 cm from the sample surface. The humidity levels of the inlet and outlet air were measured using capacitive humidity sensors (Testo 635, Germany). Three K-type thermocouples were placed at the inlet, center, and outlet of the drying chamber. During the drying process, the sample temperature was monitored at three-minute intervals using an infrared thermometer (Fluke, 62MAX, Malaysia). The main components of the system included two magnetrons (M24FA model, Galanz), each with an adjustable MW power range of 100–600 W, operating at 2.45 GHz.

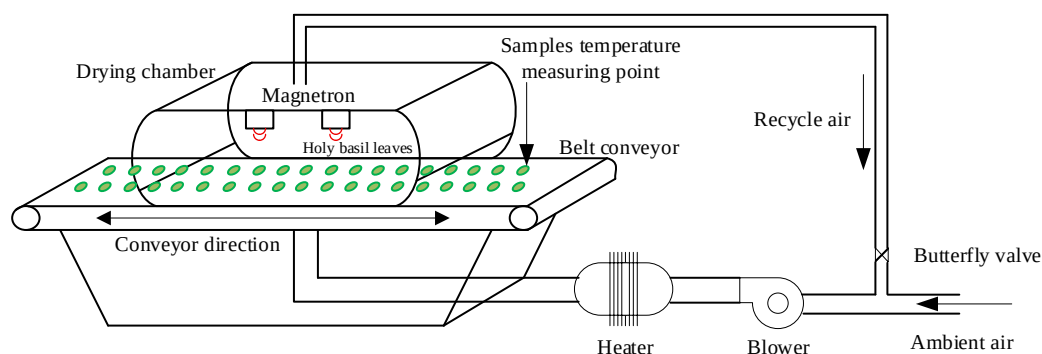


Figure 1 Schematic diagram of the combined MW-HA dryer

A centrifugal blower (TB-0400 model, 0.37 kW, 50 Hz) supplied the required airflow, while a set of U-shaped electric heaters (1 kW total power) provided convective heat. Four separate watt-hour meters (Mitsubishi MF-33E) were installed to individually measure the electrical energy consumption of the magnetrons, blower, and heaters. Its schematic diagram is shown in Figure 1.

2.2 Materials

Fresh holy basil leaves were obtained from a local agricultural supplier that followed Good Agricultural Practices (GAP) standards to ensure consistent quality and safety. Upon receipt, the leaves were immediately stored in a temperature-controlled refrigerator at 4 °C to maintain freshness and prevent quality deterioration before the experiments. A 20 g sample of fresh basil leaves was used for each drying experiment. The leaves were thoroughly washed with clean water to remove surface contaminants, then exposed to ambient air at 2–3 m/s for 5 min to remove surface moisture.

2.3 Drying procedures

Drying experiments were conducted using two methods: conventional HA drying and combined MW-HA drying. Holy basil leaves were dried under both methods at HA temperatures of 60, 70, and 80 °C, with MW power levels of 300, 400, and 500 W and a drying air velocity of 0.3 m/s. The drying apparatus consisted of a conveyor belt operated at approximately 0.02 m/s. The system had an exhaust air recirculation rate of 80%. Sample mass during drying was measured using an electronic balance (Sartorius, model BSA3202S-CW, Germany) with an accuracy of ± 0.01 g. The sample weight was measured under ambient conditions of 27 ± 2 °C and $65 \pm 5\%$ relative humidity. For each measurement, the sample was removed from the drying chamber and placed on the balance for approximately 5–10 s. This brief exposure to ambient conditions may have caused slight cooling and surface moisture changes, which represents a limitation of the experimental setup. The mass was recorded at 3-minute intervals until the moisture content of the samples was reduced to approximately 5% (d.b.). The moisture content was determined by oven-drying the samples (Memmert, Model UF75, Germany) at 103 °C for 3 h according to a procedure similar to the standard AOAC method [13]. Based on these measurements, the initial moisture content of the basil leaves was approximately 500–510% (d.b.). All experiments were conducted in triplicate, and the results are presented as mean values with standard deviations.

2.4 Simulation set-up

2.4.1 Shape and model of basil leaves

As shown in Figure 2, the geometry of the basil leaf used in the simulation was created using CATIA software. A three-dimensional model of a single holy basil leaf was developed based on the average dimensions obtained from 40 fresh leaves. The dimensions of the basil leaf model are as follows: a 30 mm width, 50 mm length, and a 0.22 mm thickness, with a surface area of 0.001916 m², a volume of 2.07835×10^{-7} m³, and a perimeter of 0.120358 m. These automatically calculated values accurately represent the physical characteristics of the basil leaves used in the experiment.

The basil leaf model was analyzed using the finite element method in COMSOL Multiphysics 3.5 to simulate the drying process. The model mesh was set to a nominal element size, which resulted in a total of 108,804 elements. This mesh configuration provided a balance between accuracy and computational efficiency and was selected to ensure reliable model performance and accurate simulation results. The simulation incorporated the thermal and physical properties of basil leaves as model input parameters. The thermophysical properties of holy basil leaves were estimated using the composition-based prediction model proposed by Choi and Okas [14]. Proximate composition of basil leaves reported by Mousavi et al. [15] was incorporated into the mixture equations to determine the moisture-dependent density (ρ_p), thermal conductivity (k_p), and specific heat capacity (C_p). These properties were calculated using the following equations: $\rho_p = 1425350/(983 + 467M)$, $k_p = 0.183 + 0.401M$, and $C_p = 1.440 + 2.747M$, where M represents the experimentally measured moisture content of basil leaves (kg/kg dry solid). The equivalent diameter of basil leaves (D_{eq}) was calculated using the following equation: $D_{eq} = 1.55A_p^{0.625}/P_p^{0.25}$, where A_p is the leaf surface area and P_p is the leaf perimeter [16]. This value was essential for modeling heat and mass transfer during drying.

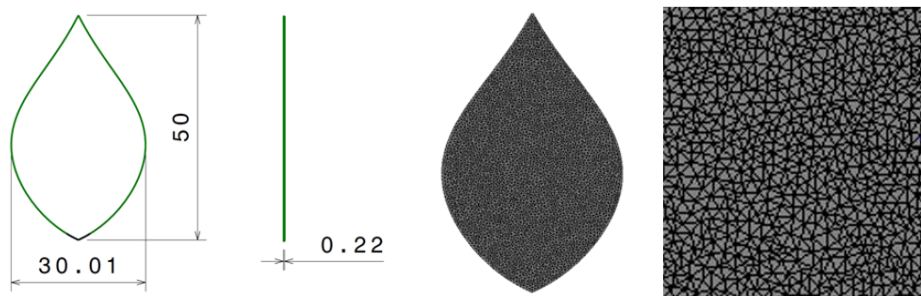


Figure 2 Shape and model of basil leaves

2.4.2 Heat and mass transfer model

A mathematical transport model was developed using COMSOL Multiphysics. The model incorporated heat and mass transfer equations based on several simplifying assumptions. Moisture-dependent thermophysical properties, including density, thermal conductivity, and specific heat capacity, were used in the model. A lumped-effective diffusivity approach was employed, and a uniform volumetric microwave heat source was assumed. Therefore, the model is more applicable to trend analysis and relative comparisons among drying conditions.

When Fourier's first law of heat conduction is applied to the first law of thermodynamics, the resulting equation is known as Fourier's second law of heat conduction. This equation describes heat transfer within a system through conduction. For three-dimensional heat transfer in the x -, y -, and z -directions, the governing equation can be expressed as:

$$\rho_p C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_p \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_p \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_p \frac{\partial T}{\partial z} \right) + Q_{gen} \quad (1)$$

where T is the sample temperature (K) at time t , ρ_p is the sample density (kg/m³), C_p is the specific heat capacity of the sample (J/kg·K), k_p is the thermal conductivity of the material (W/m·K), and Q_{gen} is the microwave heat generation rate (W/m³) [15].

Usually, most of the water remains in liquid form as drying rates are reduced. Due to the difference in water vapor concentration within the material, mass transfer in the system can be described by a moisture diffusion equation based on Fick's second law. For three-dimensional mass transfer in the x -, y -, and z -directions, the governing equation is expressed as:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left(D_{eff} \frac{\partial M}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_{eff} \frac{\partial M}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_{eff} \frac{\partial M}{\partial z} \right) \quad (2)$$

where M is the sample moisture content (% d.b.) at time t , D_{eff} is the effective moisture diffusivity coefficient (m²/s).

The MW heat source term Q_{gen} (W/m³) is defined as $Q_{gen} = 2\pi f \epsilon_0 \epsilon'' E^2$, where f is the MW frequency (Hz), ϵ_0 is the permittivity of free space (8.854×10^{-12} F/m), ϵ'' is the dielectric loss factor, and E is the electric field intensity (V/m) [17, 18]. A complete electromagnetic-thermal coupling model requires dielectric properties (ϵ' , ϵ''). For fresh holy basil, these values are estimated from the literature as $\epsilon' = 48$ –52 and $\epsilon'' = 12$ –15 at 2.45 GHz, which are comparable to those reported for other leafy herbs [19, 20]. The electromagnetic heat source was automatically calculated based on microwave power levels of 300, 400, and 500 W. The simulation employed the standard WR430 in COMSOL Multiphysics, which uses a waveguide size of 86.4 mm x 43.2 mm and a length of 86.8 mm. Heat transfer in the solid module was analyzed during a time-dependent study phase. This model is a semi-empirical approximation.

2.4.3 Initial and boundary conditions

Since the initial temperature and moisture distributions within the samples were uniform, the initial conditions can be expressed as:

$$T|_{t=0} = T_0 \quad \text{at } t = 0 \quad (3)$$

$$k_p \frac{\partial T}{\partial n} \Big|_s = h_c(T_a - T_s) + Q_{gen} + \rho_p h_{fg} \frac{V_p}{A_p} \frac{\partial M}{\partial t} \quad \text{at } t > 0 \quad (4)$$

$$M|_{t=0} = M_0 \quad \text{at } t = 0 \quad (5)$$

$$D_{wa} \frac{\partial M}{\partial n} \Big|_s = h_m(M_e - M_s) \quad \text{at } t > 0 \quad (6)$$

where T_0 is the initial temperature (K), h_c is the heat transfer coefficient ($\text{W}/\text{m}^2\cdot\text{K}$), h_{fg} is the latent heat of evaporation (J/kg), V_p is the sample volume (m^3), A_p is the sample cross-sectional area (m^2), M_0 is the initial moisture content (% d.b.), D_{wa} is the diffusion coefficient of water vapor in air (m^2/s), h_m is the mass transfer coefficient (m/s), M_e is the equilibrium moisture content (% d.b.), and M_s is the surface moisture content (% d.b.). Table 1 presents the thermal properties of air used in the model.

Table 1 Thermal properties of the air used in the model.

Name	Expression	Reference
T_a	60, 70, 80	This work
Ru	8.314	[21]
R	287	[21]
ρ_a	$101.325[kPa] / R \times (T_a + 273.15)$	[21]
c_a	$(1003.5 + (0.0129 \times T_a) + (4.0 \times 10^{-4} \times T_a^2))$	[21]
k_a	$(0.0237 + (7.53 \times 10^{-5} \times T_a) - (2.28 \times 10^{-8} \times T_a^2))$	[21]
μ_a	$((1.74 \times 10^{-5}) + (4.65 \times 10^{-8} \times T_a) - ((2.27 \times 10^{-11}) \times T_a^2))$	[21]
D_{wa}	$(2.084 \times 10^{-5}) + (1.591 \times 10^{-7} \times T_a) + ((3.153 \times 10^{-10}) \times T_a^2)$	[21]
Pr	$(\mu_a \times c_a) / k_a$	[21]
Sc	$(\mu_a) / (\rho_a \times D_{wa})$	[21]
Le	Sc / Pr	[21]
Re	$(\rho_a \times u_a \times D_{eq}) / (\mu_a)$	[21]
Nu	$C \times Re^m \times Pr^{1/3}$	[21]
h_c	$Nu \times k_a / D_{eq}$	[21]
h_m	$h_c / (\rho_a \times c_a \times Le^{2/3})$	[22]

Ru is the universal gas constant ($\text{J}/\text{mol}\cdot\text{K}$), R is the gas constant of air ($\text{J}/\text{kg}\cdot\text{K}$), ρ_a is the density of dry air (kg/m^3), T_a is the drying air temperature ($^\circ\text{C}$), c_a is the specific heat capacity of dry air ($\text{J}/\text{kg}\cdot\text{K}$), k_a is the thermal conductivity of dry air ($\text{W}/(\text{m}\cdot\text{K})$), μ_a is the dynamic viscosity of dry air ($\text{kg}/(\text{m}\cdot\text{s})$), D_{wa} is the diffusion coefficient of water vapor in air (m^2/s), Pr is the Prandtl number, Sc is the Schmidt number, Le is the Lewis number, Re is the Reynolds number, Nu is the Nusselt number, h_c is the heat transfer coefficient ($\text{W}/(\text{m}^2\cdot\text{K})$), and h_m is the mass transfer coefficient (m/s).

2.4.4 Mesh-independence study

A mesh-independence study was performed using three mesh sizes: coarse (54,402 elements), normal (108,804 elements), and fine (217,608 elements). The predicted drying time to reach 5% d.b. showed a difference of 7.2% between the coarse and normal meshes, while the difference between the normal and fine meshes was only 2.4%. The maximum temperature differed by 1.1 $^\circ\text{C}$ between the normal and fine meshes. Therefore, the normal mesh was retained. The convergence tolerances were 1×10^{-6} for temperature and 1×10^{-7} for moisture concentration.

2.5 Color evaluation

Color analysis was conducted using the CIE color scale. Three independent drying experiments were conducted for each condition, with three experimental replicates performed for each trial. For the dried samples randomly selected from all trials, five color measurements were obtained at different positions on the sample surface to account for spatial variability. The mean and standard deviation values of all color measurements were calculated, and the overall results represent the average values from the three independent drying experiments. A colorimeter (HunterLab, ColorFlex, USA) was used to measure color. Before making measurements, the colorimeter was calibrated with standard white and black plates. The average color values were reported, including the L^* value (lightness/darkness), a^* value (redness/greenness), and b^* value (yellowness/blueness). The total color change (ΔE) was calculated as:

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (7)$$

where L_0 is the lightness/darkness of the fresh sample, L^* is the lightness/darkness of the dried sample, a_0 is the redness/greenness of the fresh sample, a^* is the redness/greenness of the dried sample, b_0 is the yellowness/blueness of the fresh sample, and b^* is the yellowness/blueness of the dried sample.

2.6 Specific energy consumption evaluation

The energy efficiency of the drying process (comprising the electrical energy supplied to the blower, electric heaters, and MW system) was assessed by calculating the specific energy consumption (SEC). The SEC is a key performance indicator that quantifies the amount of energy required to evaporate a unit mass of water from a material during drying. It provides a comprehensive measure of the overall energy demand of a drying process and is essential for evaluating the efficiency of a drying method.

The SEC was calculated based on the total energy consumed during the drying process relative to the total amount of moisture evaporated. This can be expressed as:

$$SEC_{Total} = \frac{2.6(E_{Blower} + E_{MW}) + E_{Heater}}{M_w} \quad (8)$$

where SEC_{Total} is the total specific energy consumption (MJ/kg water evaporated), E_{Blower} is the electrical energy consumed by the blower (MJ), E_{MW} is the electrical energy supplied to the magnetron for microwave penetration and sample heating (MJ), E_{heater} is the energy required by the electric heater to raise the ambient air temperature to the desired level (MJ), and M_w is the amount of water removed (kg) until the final moisture reaches 5 % (d.b.). A conversion factor of 2.6 accounts for losses in electricity generation, transmission, and distribution. Equation (8) provides a meaningful comparison of the total primary energy benefits for industrial applications and enables the evaluation of energy consumption across different energy sources [23, 24].

3. Results and discussion

3.1 Drying kinetics and model prediction

Figure 3 presents the drying curves of basil leaves subjected to various drying processes. The experimental data are presented with the predictions from the developed COMSOL-based mathematical model, which enables direct visual comparison of model performance across all drying conditions.

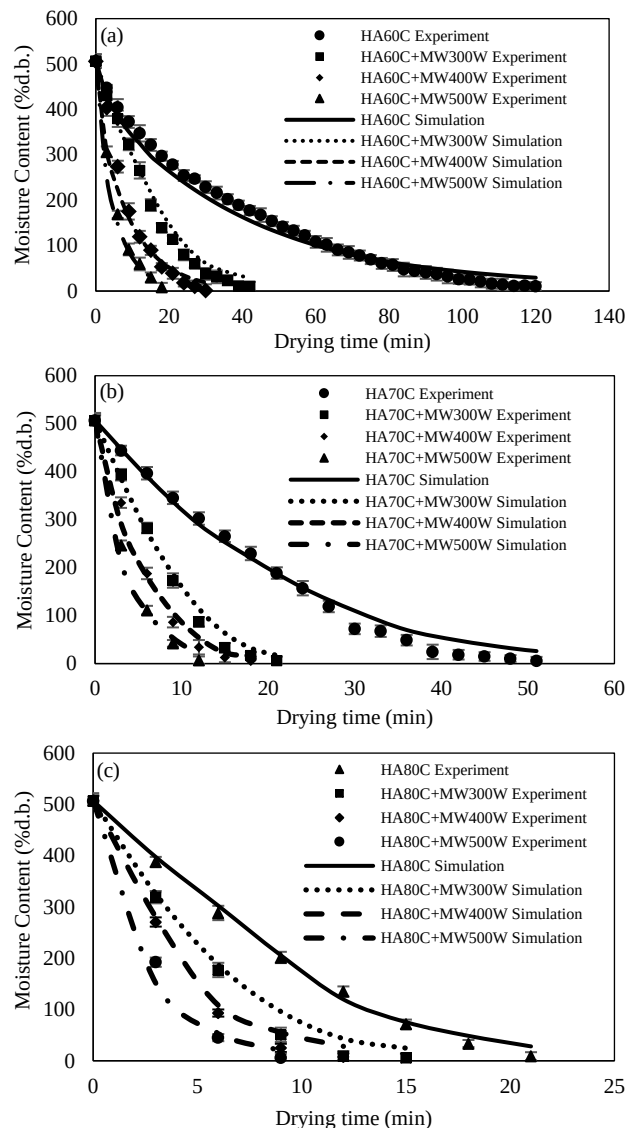


Figure 3 Drying curves of basil leaves at various HA temperatures combined with MW power levels, 300–500 W: (a) HA at 60 °C; (b) HA at 70 °C; and (c) HA at 80 °C.

For HA drying at 60 °C, as illustrated in Figure 3a, the moisture content gradually decreased from an initial value of approximately 500–510% (d.b.) to the target final moisture content of 5% (d.b.) within 114 min. The experimental data showed a smooth moisture-reduction pattern characteristic of convective drying, with the drying rate progressively decreasing as the moisture content declined. The mathematical model predictions closely followed the experimental trend throughout the drying process, demonstrating the model's capability to simulate conventional hot-air drying behavior.

MW-assisted drying at an HA temperature of 60 °C showed substantially accelerated moisture removal across all MW power levels, as shown in Figure 3a. Higher MW power substantially reduced the drying duration from 39 min at 300 W to 27 min at 400 W and further to 18 min at 500 W, resulting in a drying time reduction of up to 84% compared with traditional HA drying. This substantial improvement demonstrates that MW energy effectively accelerates surface moisture removal through volumetric heating, which generates heat directly within the material and promotes rapid evaporation. The drying curves under MW-assisted conditions exhibited steeper initial slopes, indicating enhanced drying rates during the early stages of the process. The model predictions showed good visual agreement with the experimental data across all MW power levels and closely followed the accelerated moisture reduction patterns [25].

For MW-assisted drying at a higher air temperature, 70 °C, as shown in Figure 3b, the drying time required to reach a moisture content of 5% (d.b.) ranged from 21 min at 300 W to 18 min at 400 W and 12 min at 500 W. The overall drying durations were considerably shorter than those observed at 60 °C, indicating an enhanced thermal driving force for moisture evaporation at elevated air temperatures. The experimental data showed that increasing MW power consistently reduced the drying time, with the 500 W condition achieving a 76% reduction compared with HA drying alone at the same temperature (approximately 51 min). The visual comparison between experimental data and model predictions revealed strong agreement across all conditions, with the simulated curves effectively capturing both the rapid initial drying phase and the subsequent falling-rate period.

Figure 3c illustrates the reduction in moisture during the MW-assisted drying process at 80 °C. At this elevated temperature, the drying rates were the highest among all tested conditions. MW energy further reduced the drying time by up to 57% compared with heat-assisted drying alone. Similar trends were observed during drying at 60 and 70 °C. The close visual agreement between experimental and simulated drying curves across all conditions indicates that the developed mathematical model effectively captured the essential heat and mass transfer phenomena governing the combined MW-HA drying process. The model's capability to predict moisture reduction patterns from the initial rapid drying stage to the final falling-rate period confirms its suitability for predicting drying behavior under various processing conditions. The ambient conditions during weighing were 27 ± 2 °C and $65 \pm 5\%$ relative humidity. Each weighing interruption lasted approximately 5–10 s, during which the sample was removed from the drying chamber and placed on the balance. This brief exposure to ambient air may have caused minor cooling and moisture exchange (absorption or desorption) at the sample surface. This condition represents a limitation of the experimental protocol.

Table 2 Comparison of model predictions with experimental data across all drying conditions.

Drying condition	RMSE (% d.b.)	R ²
HA60°C	16.9248	0.9915
HA60°C+MW300W	20.4708	0.9964
HA60°C+MW400W	20.6737	0.9864
HA60°C+MW500W	23.6470	0.9856
HA70°C	19.1700	0.9952
HA70°C+MW300W	16.7885	0.9972
HA70°C+MW400W	20.3916	0.9900
HA70°C+MW500W	17.5407	0.9918
HA80°C	12.0913	0.9963
HA80°C+MW300W	24.9549	0.9968
HA80°C+MW400W	18.1716	0.9995
HA80°C+MW500W	16.5829	0.9883

Table 2 compares model predictions against experimental data. Statistical analysis revealed consistently high R² values ranging from 0.9856 to 0.9995 across all drying conditions, indicating that the mathematical model explained more than 98% of the variance in the experimental data. This strong correlation quantitatively confirms the close agreement between model predictions and experimental observations, demonstrating that the mathematical transport model adequately captured the overall drying behavior of holy basil leaves under combined MW-HA conditions.

The lowest RMSE (12.0913) and a high R² (0.9963) were observed for HA drying at 80 °C, indicating the model's strongest predictive performance under conventional convective drying. Among MW-assisted conditions, the lowest RMSE (16.5829) and a high R² (0.9883) were achieved using HA at 80 °C and an MW power of 500 W, while the highest R² (0.9995) with a moderate RMSE (18.1716) was obtained using HA at 80 °C and an MW power of 400 W. The model's predictive accuracy remained satisfactory across all MW power levels, with R² values consistently above 0.9856 despite slightly higher RMSE values at higher MW power, particularly at 60 and 80 °C with an MW power of 300 W (RMSE = 24.9549), where rapid combined heating may introduce more complex drying dynamics. The statistical parameters confirm that the model provides reliable predictions. High R² values indicate a strong correlation between the predicted and experimental moisture contents. However, these values do not necessarily guarantee complete predictive accuracy, particularly during the later stages of drying, when systematic deviations were observed.

Figure 4 illustrates the temperature profiles of basil leaves under HA drying at 70 °C combined with MW power of 300–500 W. For HA drying at 70 °C, the leaf temperature reached approximately 70 °C within 15 minutes and then stabilized. This behavior is characteristic of convective heating, in which a substantial amount of energy is consumed as latent heat during moisture evaporation.

The combination of MW energy and HA drying substantially accelerated heating. At 300 W, the time required to reach the stabilizing temperature was reduced to 9 minutes. At 400 and 500 W, the stabilization times decreased further to 6 and 3 minutes, respectively. Incorporation of MW energy reduced the drying time by approximately 40–80% compared with HA drying alone. This acceleration is attributed to the volumetric heating effect of MW, which generates heat directly within the material. The simulated temperature profiles closely match the experimental data. Similar trends were observed at HA drying temperatures of 60 and 80 °C (data not shown).

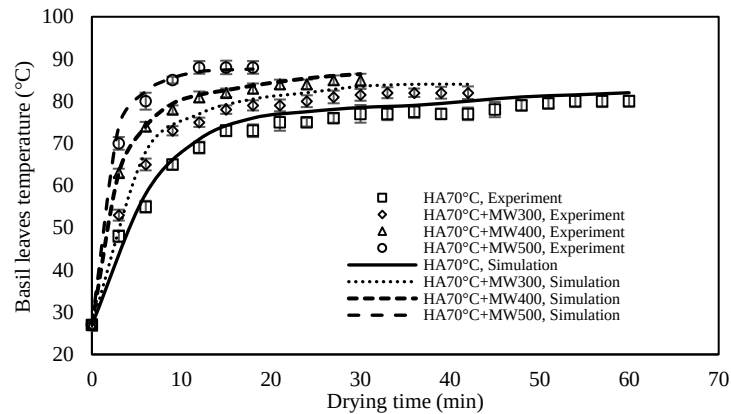


Figure 4 Experimental and simulation temperatures of basil leaves under HA at 70 °C combined with MW power of 300–500 W.

3.2 Effective moisture diffusivity

Table 3 presents the D_{eff} values for basil leaves under various drying conditions, calculated from the experimental drying curves. The D_{eff} values ranged from 1.98×10^{-12} – 2.79×10^{-11} m²/s, which represents an increase of more than ten times. Higher HA temperatures notably increased D_{eff} due to the thermal activation of water molecules and the corresponding increase in vapor pressure. In the absence of MW energy, raising the temperature from 60 to 80 °C resulted in an approximate 4.3-fold increase in D_{eff} , consistent with an Arrhenius-type relationship. The thermal effect accelerates molecular diffusion and reduces water viscosity, which in turn shortens the drying time [26].

MW augmentation produced an even greater enhancement. At 60 °C, 300 W of MW power increased D_{eff} by 166%, while an MW power input of 500 W increased D_{eff} by 618% compared with HA drying alone. This improvement is attributed to volumetric heating, which accelerates internal moisture transport. However, D_{eff} is a composite parameter that reflects various concurrent phenomena, including vapor diffusion, capillary flow, and pressure-driven flow [27]. The current data do not identify specific structural mechanisms, such as the formation of micro-channels. Direct evidence from scanning electron microscopy (SEM) imaging or porosity measurements would help validate these structural interpretations. Therefore, this study interprets the increase in D_{eff} as an overall enhancement of moisture mobility.

The combination of high temperature and MW power exhibited a synergistic effect. The maximum D_{eff} of 2.79×10^{-11} m²/s was observed at 80 °C with HA drying using an MW power of 500 W, which was 14 times greater than the value obtained with HA drying alone at 60 °C. This synergy occurs because elevated temperatures weaken the hydrogen bonds of water, while MW energy provides internal heat. Together, these factors help minimize the internal mass-transfer limitations that often occur during the later stages of drying.

Table 3 Effective moisture diffusivity coefficients of basil leaves under different drying conditions.

HA temperature (°C)	MW power (W)	D_{eff} (m ² /s)
60	n.a.	1.98×10^{-12}
	300	5.26×10^{-12}
	400	8.42×10^{-12}
	500	1.42×10^{-11}
70	n.a.	3.83×10^{-12}
	300	9.38×10^{-12}
	400	1.41×10^{-11}
	500	1.91×10^{-11}
80	n.a.	8.46×10^{-12}
	300	1.58×10^{-11}
	400	1.89×10^{-11}
	500	2.79×10^{-11}

3.3 Color of dried basil leaves

Color is a key quality attribute of dried herbs, as it directly affects consumer perception and indicates the extent of thermal and oxidative degradation during processing. Figure 5 visually compares the appearance of basil leaves dried under various conditions. Fresh basil leaves exhibited characteristic L^* , a^* , and b^* values of 24.82, -6.97, and 19.13, respectively, which reflect their bright green appearance.

Under HA drying, all dried samples showed a decrease in lightness (L^*) and a shift of a^* from negative (green) to positive (reddish) values, indicating a loss of brightness and greenness. During HA drying at 60 °C, L^* decreased to 20.13, a^* increased to 1.74, and b^* dropped to 15.00. This trend became more pronounced at higher temperatures. For example, HA at 80 °C resulted in the lowest L^* (17.78) and a^* (0.73), along with a b^* value of 10.69, confirming that elevated temperatures promote browning and darkening, likely through Maillard reactions [1, 28].

An increased MW power at a fixed HA temperature generally resulted in higher L^* values. For example, using HA at 70 °C, an increase in MW power from 300 to 500 W raised the L^* value from 23.64 to 27.51, suggesting better preservation of lightness. This is consistent with the accelerated drying kinetics and higher moisture diffusivity, which together reduce the time available for thermal degradation.

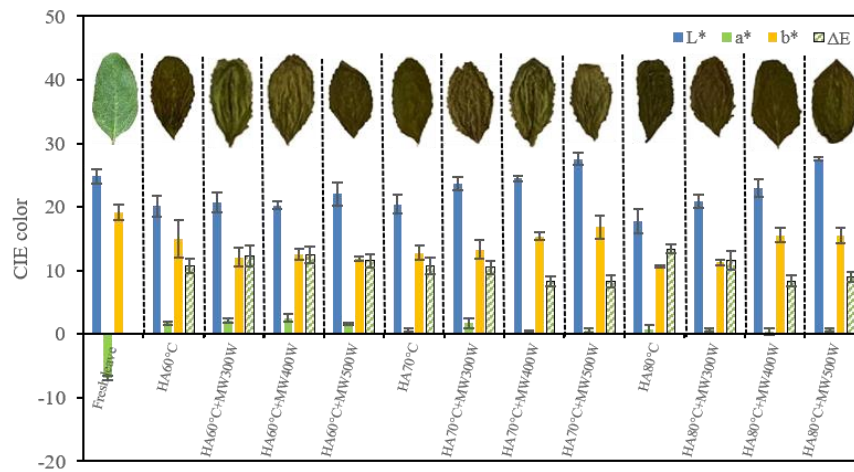


Figure 5 Color of basil leaves after drying under different conditions.

The apparent color of basil leaves in Figure 5 is a combination of the L^* , a^* , and b^* values; no single value is representative. Therefore, the total color difference (ΔE) was considered. The lowest ΔE values ranged from 8.27 to 8.93 under HA drying at 70 and 80 °C combined with MW power levels of 400 and 500 W.

3.4 Specific energy consumption

Figure 6 illustrates the SEC of the heater, MW, and blower as well as the total SEC and drying times for basil leaves under various drying conditions. The data clearly show trends in energy utilization and process efficiency, influenced by both HA temperature and MW power. Increasing the HA temperature from 60 to 80 °C reduced both drying time and total SEC. Under HA drying alone, the total SEC decreased from 1625.7 MJ/kg water evaporated at 60 °C to 583 MJ/kg water evaporated at 80 °C, a reduction of 64.1%. This decrease primarily resulted from a reduction in drying time from 114 to 21 minutes, which reduced the energy consumed by both the heater and the blower. Notably, the SEC of the heater dropped from 1426.6 MJ/kg water evaporated at 60 °C to 530 MJ/kg water evaporated at 80 °C, demonstrating the efficiency gains achieved through accelerated convective evaporation at higher temperatures.

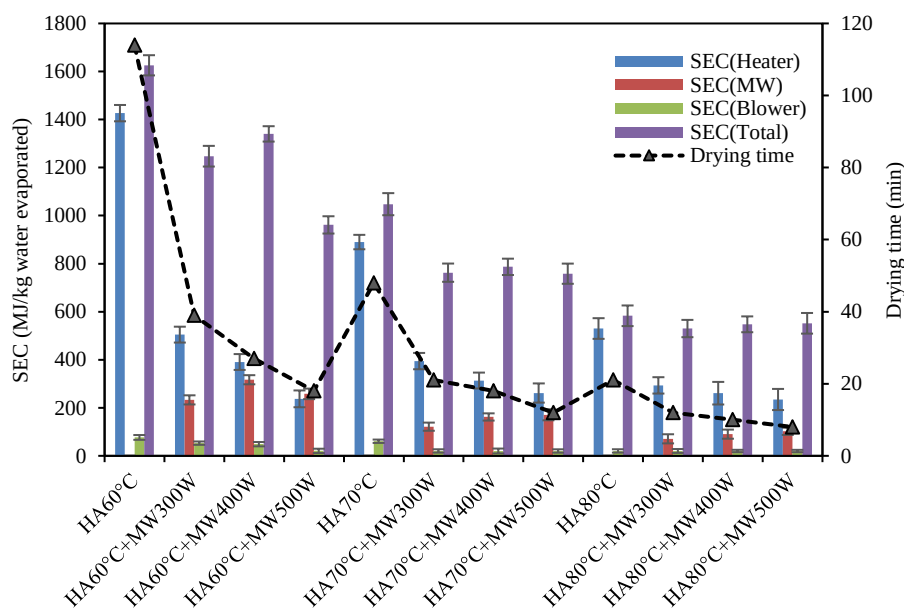


Figure 6 Specific energy consumption of the drying process and drying times under different conditions

MW energy consistently reduced the heater's SEC by shifting part of the energy load from convective to dielectric heating. For example, at 60 °C, applying 300 W of MW power reduced the heater's SEC from 1426.6 to 504.6 MJ/kg water evaporated, while the MW SEC was 232.9 MJ/kg water evaporated. Despite this additional component, the total SEC decreased from 1625.8 to 1247.3 MJ/kg water evaporated, marking a reduction of 23.3%, and drying time was shortened from 114 minutes to 39 minutes. This confirms that MW-assisted drying improves overall energy efficiency through volumetric heating, which directly targets moisture and reduces the dependence on prolonged convective heating [29]. Higher MW power further reduced drying time, but its effect on total SEC was non-linear and depended on specific conditions. At 60 °C, increasing the MW power from 300 to 500 W reduced the drying time from 39 to 18 minutes (53.8% reduction) and decreased the total SEC from 1247.3 to 961.4 MJ/kg water evaporated (22.9% reduction). However, at 70 °C, increasing the MW power from 300 to 500 W did not result in a notable change in the total SEC. This suggests that increasing MW

power beyond a certain threshold may yield diminishing returns in energy savings, as a larger portion of the energy may be absorbed by the material or lost as reflected power rather than used directly for moisture evaporation.

The lowest total SEC was achieved under the combined condition of HA at 80 °C and an MW power of 300 W, with a value of 529.91 MJ/kg_{water evaporated}, which was 67.4% lower than that of HA drying alone at 60 °C. Interestingly, increasing the MW power from 400 to 500 W at HA 80 °C slightly increased the total SEC from 547.53 to 551.71 MJ/kg_{water evaporated}, respectively, even though the drying time continued to decrease. This indicates that at high air temperatures, excessive MW input may not proportionally enhance energy efficiency due to energy losses or reduced MW absorption by the material. The relatively high SEC values may result from the small sample size, 20 g, and the energy consumption of the laboratory-scale dryer. At a commercial scale, higher energy efficiency may be achieved through improved heat recovery, continuous operation, and larger batch sizes. Therefore, the SEC values obtained in this study should be regarded as comparative laboratory data rather than direct measures of industrial energy efficiency.

4. Conclusions

The combination of MW and HA drying substantially improves the drying performance of holy basil compared with conventional HA drying alone. MW power can accelerate moisture removal by up to 84%. A mathematical transport model developed using COMSOL Multiphysics demonstrated good agreement with experimental data. Effective moisture diffusivity increased at higher temperatures and MW power levels, with values ranging from 1.98×10^{-12} – 2.79×10^{-11} m²/s. Color retention analysis indicated that MW-assisted drying at temperatures between 70 and 80 °C, with power levels of 400 to 500 W, resulted in the lowest total color difference values, 8.27–8.93. The lowest specific energy consumption was 529.91 MJ/kg_{water evaporated} at 80 °C with 300 W of MW power. The selection of drying conditions depends on the processor's priorities. For energy efficiency, 80 °C with 300 W is recommended, whereas 70–80 °C with 400–500 W of MW power is preferred for better color retention.

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6. References

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