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Impact of Cold Plasma Pretreatments on Drying Behavior and Kinetic Characteristics of Barberry under two Drying Methods (Hot air dryer Vs. Microwave)

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ABSTRACT

Barberry (*Berberis vulgaris* L.) is a highly perishable fruit due to its high moisture content. This study investigated the effect of cold plasma pretreatments, including dielectric barrier discharge (DBD; 3 and 6 min) and Glide plasma (1 and 2 min), combined with microwave and hot-air drying methods. The results showed that the drying time of the control samples was about 1280 min under hot-air drying and 15 min under microwave drying. Plasma pretreatment significantly shortened the drying time. In the DBD treatment, the drying time decreased to about 930 min in hot-air drying and 10.5–11.5 min in microwave drying, while Glide plasma reduced the drying time to approximately 1200–1230 min and 10.5–12 min under hot-air and microwave drying, respectively. On average, plasma-treated samples exhibited a 45% reduction in drying time and a 20–30% increase in drying rate compared with the control. Among the evaluated models, the Midilli et al. model provided the best fit to the experimental data with R^2 values ranging from 0.9900 to 0.999. The effective moisture diffusivity (Deff) ranged from 6.88×10^{-8} to 9.73×10^{-6} m²/s, with the highest value observed in the DBD–microwave treatment and the lowest in the Glide–hot-air combination. Overall, the findings indicate that cold plasma pretreatment, particularly when combined with microwave drying, can significantly enhance drying efficiency and mass transfer in barberry.

1- INTRODUCTION

Barberry (Berberis vulgaris L.) is a medicinal and economic fruit crop that has been widely used in traditional medicine for centuries and is extensively cultivated in Iran. Global production of barberry is concentrated in Iran, and South Khorasan alone is responsible for roughly ninety-five percent of this output. At harvest, barberry contains a substantial amount of water, which significantly limits its storage stability. As a result, drying becomes indispensable for reducing postharvest losses and ensuring product availability beyond the harvesting period [1]. Conventional hot-air drying is one of the most commonly used techniques for drying agricultural products because of its simplicity and low initial cost. However, this method is often associated with long drying times, high energy consumption, and undesirable quality degradation caused by prolonged exposure to heat. These limitations have encouraged researchers to explore alternative drying technologies that can enhance drying efficiency while maintaining product quality [2]. Microwave drying has attracted increasing attention as an efficient and rapid drying technique. In microwave drying systems, electromagnetic energy is directly absorbed by water molecules and converted into thermal energy, resulting in volumetric heating throughout the material. This heating mechanism accelerates moisture removal, shortens drying time, and improves energy efficiency compared to conventional hot-air drying. Several studies have reported that microwave drying, either alone or in combination with other techniques, can significantly enhance drying kinetics of fruits and vegetables without severe quality deterioration [3] , [4]. In recent years, non-thermal plasma technologies have emerged as promising pretreatment methods for improving drying performance. Cold plasma pretreatment, in particular, has been shown to induce physical and structural changes on the surface of biological materials, such as surface etching, formation of microchannels, and increased porosity [5]. These modifications facilitate moisture migration and mass transfer during drying, leading to reduced drying time and enhanced drying efficiency. For instance, studies on jujube slices and beetroot have demonstrated that cold plasma pretreatment significantly improves drying kinetics by increasing moisture transfer rates and effective diffusivity. In the case of jujube slices, cold plasma not only enhanced the drying rate, but also increasing bioactive compounds like flavonoids and phenolics [6]. Similarly, for beetroot, a 5-minute cold plasma pretreatment increased drying rates by 100%, reduced specific energy consumption by 24%, and improved physical properties such as shrinkage and rehydration ratio [7]. Among the various cold plasma methods, the Dielectric Barrier Discharge (DBD) method is characterized by longer treatment times and lower energy consumption, while the Glide Arc method uses higher energy in a shorter duration [7]. The aim of this research is to compare the effectiveness of these two pretreatments—DBD and Glide Arc—on the drying behavior of barberry samples, evaluating their impacts on drying kinetics, energy consumption, and preservation of bioactive compounds.

Despite the growing interest in microwave drying and cold plasma pretreatments, most studies have focused on these techniques separately, and limited information is available regarding their combined effects on the drying behavior and kinetic characteristics of barberry. In particular, comparative investigations of different cold plasma pretreatment techniques, such as Glide plasma and DBD plasma, combined with microwave and hot-air drying, are scarce. Moreover, the drying behavior of plasma-pretreated barberry has not been sufficiently described using thin-layer drying models. Therefore, the objective of this study was to investigate the effects of two plasma pretreatment techniques (Glide plasma and DBD plasma) at different exposure times on the drying behavior and drying kinetics of barberry subjected to microwave and hot-air drying. In addition, several widely used thin-layer drying models were evaluated to identify the most appropriate model for accurately describing and predicting the drying characteristics of barberry under different drying conditions

2- Materials and Methods

2.1. Materials

Fresh barberry fruits (Berberis vulgaris L.) were harvested from agricultural fields in Birjand County, Iran. After harvesting, the samples were carefully sorted and manually cleaned to remove defective fruits, including those that were damaged, discolored, decayed, or shriveled (Fig. 1). The selected barberries were then stored under refrigerated conditions (4 ± 0.5 °C) to limit physicochemical changes prior to experimentation. The initial moisture content of the fresh samples was measured by oven-drying at 105 °C for 24 h using a hot-air convection dryer, and the moisture level was determined to be 87 ± 0.1% on a wet basis.

Figure 1. Barberry fruit (*Berberis vulgaris* L.).

2.2. Plasma Pretreatment Equipment and Conditions

For each experimental run, 100 g of barberry samples were subjected to plasma pretreatment prior to drying. Two cold plasma systems, namely DBD plasma and Glide arc plasma, were employed at different exposure times according to the experimental design. Untreated samples were considered as the control. Immediately after plasma pretreatment, samples were transferred to the drying unit to minimize any post-treatment effects.

2.2.1 Dielectric Barrier Discharge (DBD) Plasma Pretreatment

A dielectric barrier discharge (DBD) cold plasma unit (Enhancedtech 15I, Kavoshyaran Co. LTD., Iran) was used with ambient air as the plasma-forming gas. The system was powered by two independent electrical supplies: a low-frequency source operating at 50 Hz with an adjustable voltage range of 0–25 kV, and a high-frequency alternating source operating at 6 kHz with a maximum output voltage of 10 kV. Plasma generation took place within a reactor consisting of two parallel electrodes measuring 22 cm × 15 cm. The bottom electrode, fabricated from stainless steel, was positioned beneath a dielectric glass layer to ensure electrical insulation and uniform discharge formation, while the upper electrode was connected to the high-frequency power supply. The lower electrode was supplied by the low-frequency source, enabling the formation of a stable and spatially uniform plasma over the surface of the samples.[8]. Barberry samples (100 g) were uniformly spread between the electrodes and subjected to plasma pretreatment for 3 and 6 min, according to the experimental design. These exposure times were selected based on preliminary trials and previous studies to achieve effective surface modification without causing visible surface damage. After plasma pretreatment, the samples were immediately transferred to the drying unit to minimize any post-treatment effects [9].

2.2.2. Glide Arc Cold Plasma Pretreatment

Glide plasma pretreatment was carried out using a Glide arc discharge system operating at an input power of 400 W and an electric current of 2 A. The plasma reactor consisted of two diverging electrodes with an inter-electrode gap of 2 cm, generating a stable non-thermal plasma discharge. The distance between the electrode tips and the surface of the barberry samples was maintained at approximately 30 mm to ensure uniform plasma exposure. Barberry samples (100 g) were exposed to Glide arc plasma for 1 and 2 min, according to the experimental design. During treatment, samples were turned halfway through the exposure time to ensure plasma interaction on both sides. These exposure durations were selected based on preliminary experiments and previous studies to achieve effective plasma treatment without causing visible surface damage or excessive heating. Untreated samples were used as the control. Immediately after Glide arc plasma pretreatment, the samples were transferred to the drying equipment to minimize any delay between pretreatment and drying [10].

2.3 Drying Equipment and Drying Conditions

2.3.1 Microwave Drying

Microwave drying of barberry samples was performed using a domestic microwave oven (Model M945, Samsung, Korea) operating at 2450 MHz with a rated maximum power of 1000 W. Experiments were conducted under a fixed power level of 400 W, a value commonly used in previous studies and selected as a safe level that prevents quality loss or localized burning during microwave drying [11]. Sample mass variation was monitored every 30 s using a precision balance (GF-600, A&D, Japan; ± 0.01 g accuracy). The drying procedure was continued until the final moisture content of each sample decreased below 20% on a wet basis [12] .

2.3.2 Hot air dryer

Hot-air drying experiments were carried out using a laboratory-scale hot-air dryer with an internal volume of 55 L and a maximum power rating of 800 W. The external dimensions of the dryer were 52 × 41 × 70 cm (W × D × H), while the drying chamber measured 40 × 33 × 42 cm. The unit was equipped with a PID-based control system to maintain stable operating conditions. Drying was conducted at a controlled air temperature of 70 ± 5 °C, a widely used non-destructive temperature that maintains product quality and minimizes anthocyanin degradation [1]. An air velocity of 0.5 m s^{-1} was applied. Sample mass was measured at 30-min intervals throughout the drying process using a digital balance (GF-600, A&D, Japan; ± 0.01 g accuracy). The drying process was terminated when the moisture content of the samples decreased to below 20% on a wet basis [2].

2.4. Pretreatments before Drying

For each experimental run, 100 g of barberry samples were subjected to plasma pretreatment. The applied pretreatments included Glide plasma for 1 and 2 min, and DBD plasma for 3 and 6 min. Untreated samples were used as the control. After plasma pretreatment, samples were immediately subjected to drying experiments. The treatments investigated in this study are summarized in Table 1.

Table 1: Treatments studied

Code	Pretreatment	Drying Method
T1	Control	Hot air dryer
T2	Control	Microwave
T3	Glide 1 min	Hot air dryer
T4	Glide 1 min	Microwave
T5	Glide 2 min	Hot air dryer
T6	Glide 2 min	Microwave
T7	DBD 3 min	Hot air dryer
T8	DBD 3 min	Microwave
T9	DBD 6 min	Hot air dryer
T10	DBD 6 min	Microwave

2.5 Drying Kinetics and Mathematical Modeling

Barberry samples (100 g) were subjected to drying using a microwave dryer operating at 400 W and a hot-air dryer maintained at 70 °C. The sample mass was measured in triplicate at regular intervals until no further change in weight was observed, and the average readings were used for subsequent analyses. The initial moisture content of each treatment was determined following the standard gravimetric procedure, and the moisture content (MC) was computed using the following equation.

$$\text{Moisture Content (MC, \%wb)} = \frac{\text{Ww}-\text{Wd}\times 100}{\text{Ww}} \quad (1)$$

The parameters Ww and Wd indicate the weights of the samples prior to and after drying, whereas wb stands for the wet-basis moisture fraction. Equilibrium moisture content (EMC) was assessed by prolonging drying until a constant mass was obtained on repeated weighing.

2.5.1 Moisture Ratio

The moisture ratio (MR) was determined from moisture content measurements collected at successive drying times under different temperature conditions. The experimentally obtained drying data were then applied to calculate both the moisture ratio (MR) and the drying rate (DR) using the equations presented below.

$$\text{Moisture Ratio MR} = \frac{\text{Mt}-\text{Me}}{\text{Mo}-\text{Me}} \quad (2)$$

In these expressions, Mt represents the moisture content at a given drying time, M0 denotes the initial moisture content, and Me refers to the equilibrium moisture content (kg water/kg dm). The drying rate (DR) is defined as kg water per kg dry matter per minute, Mt+dt is the moisture content at time t + dt, and t indicates the drying duration (min). Because the equilibrium moisture content (Me) was negligible in comparison with Mt and M0, Eq. (2) was simplified to Mt/M0. The resulting moisture ratio was subsequently used to analyze the drying kinetics of barberry through appropriate mathematical models[13].

2.5.2 Drying Rate

The drying rate (DR) was determined from the variation in moisture content over successive drying intervals using Eq. (3).

$$\text{Drying Rate DR} = \frac{\text{M(t+dt)}-\text{Mt}}{\text{dt}} \quad (3)$$

In this relation, Mt corresponds to the moisture content at time t, M(t+dt) is the moisture content measured at time t + dt, and dt denotes the elapsed time between two consecutive measurements.

2.6 Mathematical Modeling

Seven commonly applied thin-layer drying models listed in Table 1 were examined to identify the most suitable model for representing the drying behavior of barberry. Model performance was assessed by comparing experimental and predicted moisture ratio values using statistical indicators, including the coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ^2). The mathematical definitions of these statistical criteria are presented [14].

$$R^2 = \frac{\sum_{i=1}^{N}\sum(\text{MRi}-\text{MRpre,i})\times(\text{MRi}-\text{MRexp,i})}{\sqrt{\sum_{i=1}^{N}[\text{MRi}-\text{MRpre,i}]^2\times\left[\sum_{i=1}^{N}[\text{MRi}-\text{MRexp,i}]^2\right]}}$$

(5)

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

(6)

In these expressions, N represents the total number of experimental data points, z denotes the number of model parameters, and MR_exp and MR_pre correspond to the measured and calculated moisture ratio values, respectively.

Table 2- Thin-layer drying models

Model name*	Model	References
Newton	MR=exp(-kt)	[15]
Page	$MR=exp(-kt^n)$	[16]
Modified Page	$MR=exp(-(kt)^n)$	[17]
Logarithmic	MR=a exp(-kt) + b	[18]
Henderson and Pabis	MR=aexp(-kt)	[19], [20]
Midilli et al.	$MR=a\ exp(-kt^n) + bt$	[21], [22]
Wang and Singh	$MR = 1 + bt + at^2$	[23]

*Where, k is the drying constant and a, b, n are equation constants

2.7 Determination of Effective Diffusivity Coefficients

During the drying operation, moisture migration toward the material surface was assumed to occur predominantly through diffusion, which can be mathematically described using Fick's second law for a slab geometry [12].

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial x^2} \quad (7)$$

By applying suitable initial and boundary conditions, Crank developed analytical solutions for moisture diffusion in materials with different geometrical shapes. For a spherical geometry assuming constant diffusivity, the corresponding solution can be expressed as follows:

$$MR = \frac{8}{\pi^2}\sum\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)\pi^2 D_{eff}}{4L^2}t\right) \quad (8)$$

In this formulation, D_{eff} denotes the effective moisture diffusivity (m²/s), while L represents the half-thickness of the slab (m). At extended drying times, the contribution of higher-order terms in the series solution becomes negligible; therefore, retaining only the first term (n = 0) provides an accurate approximation, which can be conveniently expressed in a logarithmic form as shown below.

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\right)t \quad (9)$$

By neglecting the higher-order terms in Equation (8) and retaining only the first component of the series, the moisture diffusivity of barberry was simplified and expressed as shown in Equation (9).

In this context, the effective diffusivity (D_{eff}) was determined from the slope (K) of the linear plot obtained between ln(MR) and drying time (t). The ln(MR) versus time relationship yielded a straight line with a negative gradient, where K is mathematically linked to Deff through Equation (10).

$$K = \frac{\pi^2 Deff}{r^2} \quad (10)$$

The volume (V) of an individual barberry fruit was measured using the toluene displacement technique applied to a sample of 100 berries. The equivalent radius of a single barberry was then calculated by equating its measured volume to that of a sphere, resulting in an effective radius (r_e) of 3.57×10^{-4} m.

$$V = \tfrac{4}{3}\pi r_e^3 \quad (11)$$

3-RESULTS AND DISCUSSION

3.1 Moisture Ratio versus Drying Time

The initial moisture content of fresh barberry samples was approximately 74.55% (w.b.), indicating a high water content that strongly influenced the drying behavior. Figures 2 and 3 illustrate the variations in moisture ratio (MR) and drying rate (DR) as a function of drying time for plasma-pretreated and untreated samples subjected to microwave and hot air drying. As shown in Figure 2, the drying curves of all treatments exhibited a biphasic pattern, consisting of an initial rapid moisture removal stage followed by a falling-rate period. This behavior is typical of high-moisture agricultural products and reflects the dominance of surface evaporation in the early stage and internal moisture migration during the later stages of drying [12] .The results also demonstrated that the drying time of barberry was significantly affected by both plasma pretreatment and the drying method. The control sample under hot air drying required the longest drying time (1280 min), whereas the same sample was dried within only 15 min using microwave drying, highlighting the strong effect of volumetric heating in accelerating moisture removal. Glide arc plasma pretreatment produced a limited reduction in drying time, decreasing it to 1200–1230 min in hot air drying and to 12–10.5 min in microwave drying. In contrast, DBD plasma pretreatment showed a stronger influence, reducing the drying time to 930 min in hot air drying and to 11.5–10.5 min in microwave drying. Plasma-treated samples consistently exhibited lower moisture ratios at the same drying time compared with untreated samples, indicating enhanced drying efficiency. This improvement can be attributed to plasma-induced surface modification, including micro-etching and increased surface porosity, which facilitate moisture diffusion and reduce mass transfer resistance during drying [24]. Overall, microwave drying showed the fastest moisture removal, and the combination of DBD plasma pretreatment with microwave drying resulted in the shortest drying time, suggesting a synergistic effect between plasma-induced surface modification and the volumetric heating mechanism of microwave energy.

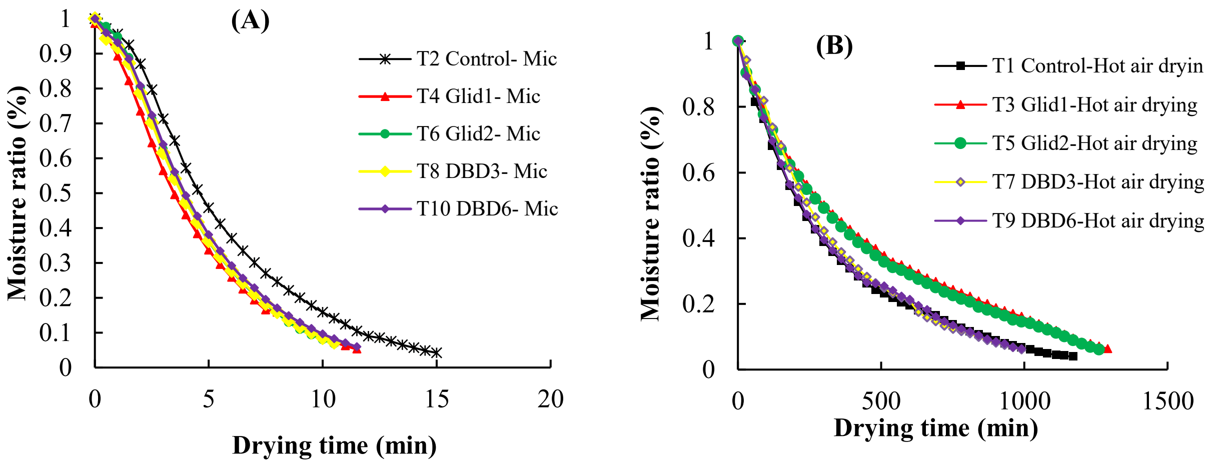

Fig. 2: Variation of moisture ratio with drying time for the barberry (A: Microwave drying, B: hot air drying)

3.2 Drying Rate Characteristics

Figure 3 presents the variation of drying rate with drying time for barberry samples. For both drying methods, the drying rate was highest at the beginning of the process due to the high initial moisture content and gradually decreased as drying progressed.

In microwave drying, the initial drying rate was substantially higher than that of hot air drying, reflecting the rapid energy absorption by free water molecules. As moisture content decreased, the drying rate declined due to reduced microwave absorption and increased resistance to moisture movement.

Plasma pretreatment led to higher drying rates during the initial and intermediate drying stages, especially under microwave drying conditions. This effect was more evident for DBD-treated samples, indicating a synergistic interaction between plasma pretreatment and microwave heating. The enhanced drying rate can be explained by the plasma-induced disruption of the outer waxy layer and cell wall structures, which reduces resistance to moisture transport[25].

In hot air drying, although the overall drying rate was lower than microwave drying, plasma-pretreated samples still exhibited improved drying performance compared to the control. This confirms that plasma pretreatment is effective regardless of the drying method, although its impact is more pronounced under microwave drying.

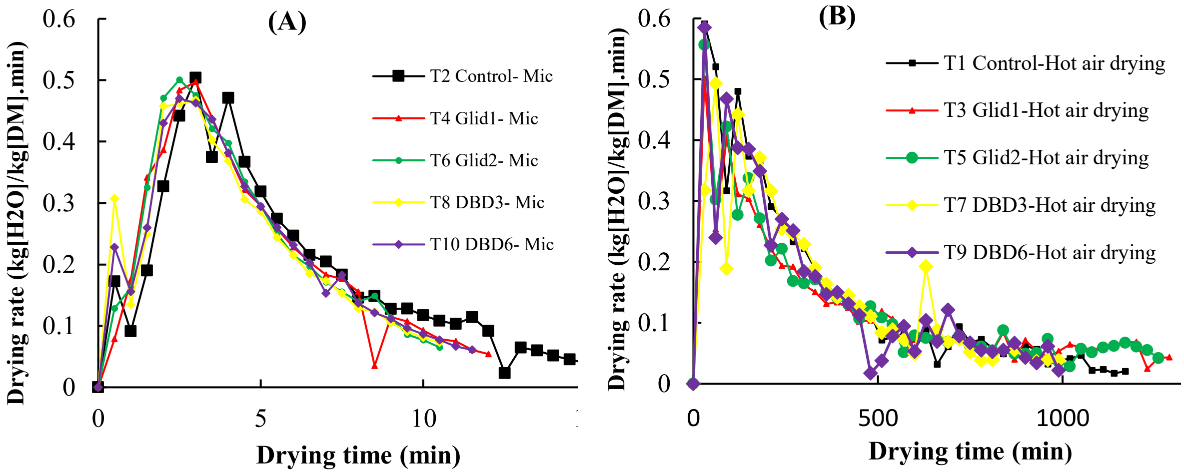

Fig. 3: Variation of drying rate with drying time for barberry (A: Microwave Drying, B: hot air drying)

3.3 Thin-Layer Drying Model Evaluation

Seven thin-layer drying models were evaluated to describe the drying kinetics of barberry under different pretreatment and drying conditions. The statistical parameters R^2, χ^2, and RMSE for all models are summarized in Table 3. Across all treatments and drying methods, the Midilli et al. model consistently provided the best fit to the experimental data, with R^2values ranging from 0.9900 to 0.9999, and the lowest RMSE and χ^2values. This high level of agreement indicates that the Midilli model is capable of accurately capturing the complex drying behavior of barberry, including the combined effects of plasma pretreatment and drying method. The superior performance of the Midilli model can be attributed to its flexible structure, which incorporates both exponential and linear terms, allowing it to effectively describe both the initial rapid drying phase and the subsequent falling-rate period. In contrast, simpler models such as Newton and Henderson–Pabis showed lower predictive accuracy, particularly for plasma-treated samples where drying behavior deviated from simple exponential decay. Model predictions closely followed the experimental moisture ratio data, as illustrated in Figure 4, confirming the suitability of the Midilli et al. model for process simulation, optimization, and design of barberry drying operations [25]. The linear behavior observed in the ln(MR) versus time plots (Fig 4) confirms the validity of the diffusion-based approach for describing moisture transfer during the falling-rate drying period. The steeper slopes observed for plasma-pretreated samples, particularly under microwave drying, indicate higher effective moisture diffusivity, which is consistent with the Deff values reported in Table 4.

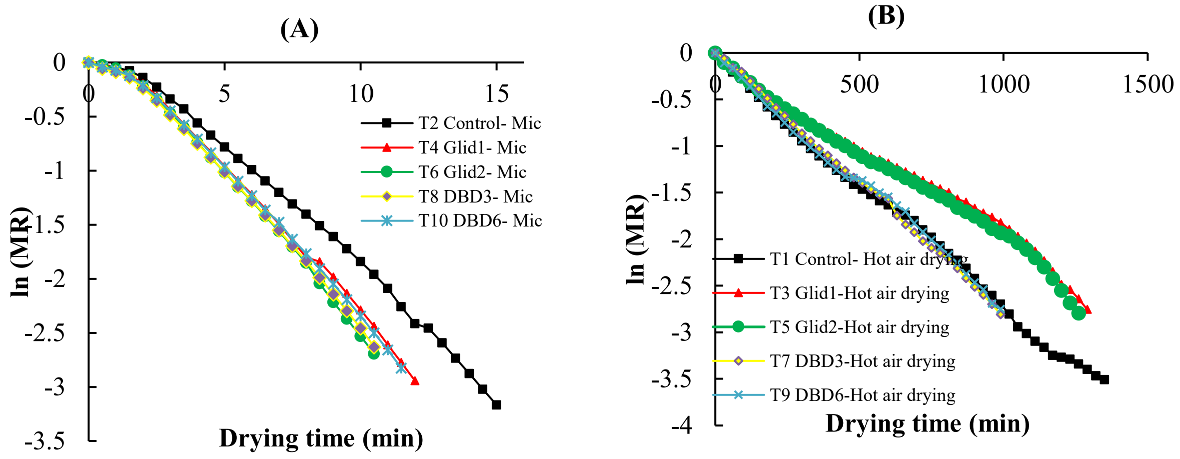

Figure 4. Ln (MR) versus time (min) for barberries at different treatment (A: Microwave Drying, B: hot air drying)

Table3: Results of statistical analysis on the modeling of moisture content and drying time for barberry

Variable	Model	R^2	χ^2	RMSE	k	n	a	b	c
T1 Control-hot air drying	Newton	0.994	0.0154	0.0199	0.002932	0	0	0	0
	Page	0.9985	0.0039	0.0102	0.005396	0.08987	0	0	0
	Modified Page	0.9985	0.0039	0.01	0.003	0.8981	0	0	0
	Logarithmic	0.9976	0.0062	0.013	0.003143	0	0.9501	0	0.03249
	Henderson and Pabis	0.9958	0.0109	0.017	0.002816	0	.9629	0	0
	Midilli	0.9986	0.0037	0.0101	0.0060	0.8809	1.013	-1.73×10^{-6}	0
	Wang and Singh	0.948	0.1349	0.596	0	0	-0.00211	1.77×10^{-6}	
T2 Control-Mic	Newton	0.961	0.1206	0.0634	0.1622	0	0	0	0
	Page	0.9961	.012	.0203	.0734	1.419	0	0	0
	Modified Page	0.9961	0.012	0.0203	0..1588	1.419	0	0	0
	Logarithmic	0.9889	.0343	0.035	0.1405	0	1.231	0	-0.1338
	Henderson and Pabis	0.9812	0.0582	0.0448	0.1841	0	1.135	0	0
	Midilli	0.9977	0.0072	0.163	0.07475	1.457	1.02	0.0023	0
	Wang and Singh	0.986	0.0434	0.0387	0	0	-0.1236	0.0039	0
T3 Glide1-hot air drying	Newton	0.9866	0.0348	0.0284	0.00205	0	0	0	0
	Page	0.9972	0.0074	0.0132	0.005031	0.858	0	0	0
	Modified Page	0.9971	0.0074	0.0131	0.0021	0.8573	0	0	0
	Logarithmic	0.9943	0.0148	0.019	0.002159	0	0.9151	0	0.04166
	Henderson and Pabis	0.9927	0.019	0.021	0.001951	0	0.9474	0	0
	Midilli	0.9983	0.004	0.0105	0.000845	0.0.7643	1.018	-4.49×10^{-5}	0
	Wang and Singh	09551	0.1162	0.0526	0	0	-0.0016	-7.63×10^{-7}	0
T4 Glide1-Mic	Newton	0.9569	0.1094	0.9569	0.1898	0	0	0	0
	Page	0.9964	0.0092	0.02	0.08741	1.453	0	0	0
	Modified Page	0.9964	0.0092	0.02	0.1869	1.543	0	0	0
	Logarithmic	0.9881	0.03	0.037	0.1585	0	1.263	0	-0.1646
	Henderson and Pabis	0.9791	0.0529	0.9782	0.2163	0	1.138	0	0
	Midilli	0.9985	0.0037	0.0132	0.08859	1.511	1.021	0.0038	0

	Wang and Singh	0.9839	.041	0.0422	0	0	-0.1448	0.0054	0
T5 Glide2-hot air drying	Newton	0.9866	0.0338	0.0284	0.00215	0	0	0	0
	Page	0.9982	0.0044	0.0104	0.005494	0.8513	0	0	
	Modified Page	0.9869	0.0331	0.0281	0.002	0.8754	0	0	0
	Logarithmic	0.9937	0.016	0.0195	0.002	0	0.9344	0	0
	Henderson and Pabis	0.9989	0.0028					-2.95×10^{-5}	0
				0.0083	0.0075	0.0028	1.009		
	Midilli	0.9542	0.1153	0.053	0	0	-0.00172	8.33×10^{-7}	0
T6 Glide2-Mic	Newton	0.9532	0.1028	0.0699	0.1968	0	0	0	0
	Page	0.9973	0.006	0.0173	0.08955	1.48	0	0	0
	Modified Page	0.9973	0.006	0.0173	0.1658	1.48	0	0	0
	Logarithmic	0.9888	0.0246	0.036	0.1468	0	1.339	0	-0.2519
	Henderson and Pabis	0.9761	0.525	0.0512	0.2243	0	1.133	0	0
	Midilli	0.9987	0.0028	0.0125	0.09064	1.535	1.016	0.0041	0
	Wang and Singh	0.9839	0.0352	0.042	0	0	-0.1481	0.0054	0
T7 DBD3-hot air drying	Newton	0.9983	0.0043	0.0114	0.00272	0	0	0	0
	Page	0.9985	0.0037	0.0108	0.00239	10.024	0	0	
	Modified Page	0.9983	0.0042	0.0113	0.00272	1.029	0	0	0
	Logarithmic	0.9987	0.0030	0.0102	0.0028	0	1.016	0	-0.00049
	Henderson and Pabis	0.9987	0.0033	0.0101	0.002814	0	1.017	0	
	Midilli	0.9988	0.0031	0.0101	0.0024	1.029	1.012	1.3×10^{-5}	0
	Wang and Singh	0.9887	0.0282	0.0297	0	0	-0.00216	1.28×10^{-6}	0
T8 DBD3-Mic	Newton	0.9632	0.076	0.0602	0.1978	0	0	0	0
	Page	0.9980	0.0042	0.0145	0.1012	1.408	0	0	0
	Modified Page	0.998	.0042	0.0145	0.1965	1.408	0	0	0
	Logarithmic	09905	0.0197	0.0322	0.1475	0	1.298	0	-0.2324
	Henderson and Pabis	0.9793	0.0427	0.0462	0.2205	0	1.108	0	0
	Midilli	0.9988	0.0026	0.0119	0.0943	1.5	0.9984	0.0041	0
	Wang and Singh	0.9892	0.0224	0.0334	0	0	-0.1511	0.0058	0
T9 DBD6-hot air drying	Newton	0.9983	0.0043	0.0114	0.002764	0	0	0	0
	Page	0.9985	0.0037	0.0108	0.00239	1.024	0	0	0
	Modified Page	0.9985	0.0037	0.0108	0.002756	1.024	0	0	0
	Logarithmic	0.9987	0.0032	0.0102	0.002586	0	1.014	0	0.00607
	Henderson and Pabis	0.9987	0.0033	0.0101	0.002814	0	1.017	0	0
	Midilli	0.9988	0.0031	0.0101	0.002406	1.029	1.012	1.32×10^{-5}	
	Wang and Singh	0.9887	0.0282	0.0297	0	0	-0.00216	1.289×10^{-6}	
T10 DBD6	Newton	0.9608	0.0918	0.0632	0.1915	0	0	0	0
	Page	0.9978	0.0052	0.0154					0
					0.09241	1.43	0	0	
	Modified Page	0.9978	0.0052	0.0154	0.1891	1.43	0	0	0
	Logarithmic	0.9897	0.0242	0.0339	0.1507	0	1.275	0	-0.1963
	Henderson and Pabis	0.9792	0.0487	0.0471	0.2155	0	1.121	0	0
	Midilli	0.9989	0.0026	0.0115	0.08854	1.506	1.006	0.0036	0
	Wang and Singh	0.9876	0.029	0.0363	0	0	-.0146	0.0054	0

3.4 Effective Moisture Diffusivity (D_{eff})

The effective moisture diffusivity (D_{eff}) was estimated from the experimental drying results by applying Fick's second law for spherical geometry. In the analysis, constant diffusivity, uniform initial moisture distribution, and negligible sample shrinkage were assumed. At sufficiently long drying times, the analytical solution of Fick's equation reduces to a linear form, allowing Deff to be determined from the slope of the ln(MR) versus drying time plot. The calculated Deff values corresponding to different treatments are summarized in Table 3. As shown, plasma pretreatment markedly increased Deff compared to the untreated control samples under both drying methods. This enhancement indicates improved internal moisture transport resulting from plasma-induced physical modifications of the barberry surface and near-surface structure. Among plasma treatments, DBD plasma exhibited higher Deff values than Glide arc plasma at comparable drying conditions. The highest diffusivity recorded was $9.73 \times 10^{-6}\ \mathrm{m^2/s}$for DBD plasma pretreated samples under microwave drying, while the lowest value of $6.88 \times 10^{-8}\ \mathrm{m^2/s}$was observed for Glide arc treatment in the hot air dryer. This behavior can be attributed to the more uniform discharge and stronger surface etching associated with DBD plasma, which promotes the formation of micro-channels and increases effective porosity, thereby reducing internal resistance to moisture diffusion. In addition, microwave drying resulted in significantly higher Deff values than hot-air Hot air dryer drying for all treatments. For instance, the microwave drying of untreated samples yielded $7.90 \times 10^{-6}\ \mathrm{m^2/s}$, significantly greater than the $9.78 \times 10^{-8}\ \mathrm{m^2/s}$ observed with hot air drying. The volumetric heating mechanism of microwave drying accelerates internal moisture movement by generating internal vapor pressure gradients, which synergistically interact with plasma-induced surface modification. Consequently, the highest Deff values were observed for DBD plasma-pretreated samples dried using microwave heating. The observed Deff values fall within the typical range reported for high-moisture agricultural products, confirming the physical validity of the diffusion-based approach used in this study. These results demonstrate that plasma pretreatment, particularly DBD plasma combined with microwave drying, effectively enhances internal moisture diffusion and overall drying performance.

Table 4. Effective moisture diffusivity and correlation for the performed treatment.

Treatment	D_{eff}	R^2
T1 Control-Hot air dryer	9.77626×10^{-8}	0.9958
T2 Control- Microwave	7.90067×10^{-6}	0.9958
T3 Glide1-Hot air dryer	6.87959×10^{-8}	0.987
T4 Glide1- Microwave	9.22227×10^{-6}	0.992
T5 Glide2-Hot air dryer	7.24167×10^{-8}	0.9894
T6 Glide2- Microwave	9.24762×10^{-6}	0.9885
T7 DBD3-Hot air dryer	1.01383×10^{-7}	0.9987
T8 DBD3- Microwave	9.38883×10^{-6}	0.9903
T9 DBD6-Hot air dryer	9.41418×10^{-8}	0.9939
T10 DBD6- Microwave	9.72919×10^{-6}	0.9911

3.5 Effect of Plasma Pretreatment and Drying Method Interaction

The results clearly demonstrate that the interaction between plasma pretreatment and drying method plays a crucial role in determining drying performance. While both Glide arc and DBD plasma improved drying behavior, DBD plasma exhibited a stronger effect, particularly when combined with microwave drying. Microwave drying of plasma-pretreated samples resulted in the shortest drying times and highest drying rates, highlighting the potential of this combined approach for industrial applications where time and energy efficiency are critical. The observed improvements confirm that plasma pretreatment acts as an effective physical modification technique that enhances moisture removal without the need for chemical additives [26], [27].

4- Conclusion

This study examined the influence of two cold plasma pretreatments (DBD and Glide Arc) on the drying behavior of barberry (Berberis vulgaris L.) in combination with microwave and hot-air drying methods. The results showed that plasma pretreatment markedly enhanced the drying efficiency, with DBD plasma exhibiting a stronger effect than Glide Arc. The integration of plasma pretreatment—particularly DBD—with microwave drying resulted in the shortest drying times and the highest drying rates, confirming the synergistic interaction between microwave volumetric heating and plasma-induced surface modification. Modeling of the experimental drying data demonstrated that the Midilli model provided the most accurate fit, with high coefficients of determination (R^2 = 0.9900–0.999) and the lowest error indices among the evaluated models, indicating its superior capability in describing the drying kinetics under different treatment conditions. In addition, the effective moisture diffusivity (Deff) was significantly influenced by both plasma pretreatment and drying method. The highest Deff value (9.73×10^{-6} m²/s) was achieved in DBD-treated samples dried with microwave heating, whereas the lowest value (6.88×10^{-8} m²/s) occurred in Glide Arc treated samples dried with hot air. These results highlight the strong enhancement of internal mass transfer achieved through plasma pretreatment, especially when coupled with microwave drying. Overall, the findings of this study emphasize the potential of plasma pretreatment as an effective strategy for enhancing drying processes, contributing to energy and time savings, as well as preserving the nutritional and medicinal properties of barberry for commercial and industrial applications.

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Conflict of Interest

The authors have no conflicts of interest

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All activities were carried out by the authors.

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چکیده

زرشک (*Berberis vulgaris* L.) به دلیل رطوبت بالای خود، میوه‌ای بسیار فسادپذیر است. در این پژوهش، اثر پیش‌تیمارهای پلاسما سرد شامل تخلیه سد دی‌الکتریک (DBD؛ به مدت ۳ و ۶ دقیقه) و پلاسما گلاید (به مدت ۱ و ۲ دقیقه) در ترکیب با روش‌های خشک‌کردن مایکروویو و هوای گرم مورد بررسی قرار گرفت. نتایج نشان داد که زمان خشک‌کردن نمونه‌های شاهد در روش هوای‌گرم حدود ۱۲۸۰ دقیقه و در روش مایکروویو حدود ۱۵ دقیقه بود. پیش‌تیمار پلاسما به‌طور معنی‌داری زمان خشک‌کردن را کاهش داد. در تیمارDBD ، زمان خشک‌کردن در هوای گرم به حدود ۹۳۰ دقیقه و در مایکروویو به حدود ۱۰/۵ تا ۱۱/۵ دقیقه کاهش یافت، در حالی که پلاسما گلاید زمان خشک‌کردن را به‌ترتیب به حدود ۱۲۰۰ تا ۱۲۳۰ دقیقه در هوای گرم و ۱۰.۵ تا ۱۲ دقیقه در مایکروویو کاهش داد. به‌طور میانگین، نمونه‌های تیمار شده با پلاسما در مقایسه با شاهد، ۴۵٪ کاهش در زمان خشک‌کردن و ۲۰ تا ۳۰٪ افزایش در نرخ خشک‌کردن نشان دادند. در میان مدل‌های مورد بررسی، مدل میدیلی و همکاران بهترین انطباق را با داده‌های تجربی داشت و مقادیر ضریب تعیین (R^2) بین ۰/۹۹ تا ۰/۹۹۹ به دست آمد. ضریب نفوذ مؤثر رطوبت (Deff) در بازه ۶/۸۸ × 10^{-8} تا ۹/۷۳ × 10^{-6} متر مربع بر ثانیه قرار داشت که بیشترین مقدار مربوط به تیمارDBD مایکروویو و کمترین مقدار مربوط به ترکیب گلاید–هوای گرم بود. به‌طور کلی، نتایج نشان داد که پیش‌تیمار پلاسما سرد، به‌ویژه در ترکیب با خشک‌کردن مایکروویو، می‌تواند به‌طور قابل‌توجهی کارایی خشک‌کردن و انتقال جرم در زرشک را بهبود دهد.