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Effect of different drying techniques on the drying characteristics of celery

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Present study investigates the impact of various drying methods on the drying characteristics of celeriac, focusing on parameters like drying rate, moisture loss, and time efficiency. Understanding these kinetic aspects is essential for optimizing drying processes and improving the quality of the final product.

Two drying techniques were applied to reduce moisture content of celery. 55, 65, and 75 ˚C in a cabinet dryer, and at 62, 74, 88 and 104 W power levels in an infrared dryer were chosen as drying conditions. To understand pretreatment effect 1% citric acid solution was used. The variation in moisture content during the drying of celery samples was analyzed using eight different mathematical models. Model efficiency was assessed utilizing statistical indicators such as the coefficient of determination (R^2), root mean square error (RMSE), and chi-square (χ^2) analysis. Among the models considered, the Midilli & Küçük model yielded the closest correlation with the experimental data, indicating its superior ability to characterize the drying behavior of the samples. The estimated effective moisture diffusivity (D_{eff}) for celery dried in a cabinet dryer varied between 1.701×10^{-10} and 3.317×10^{-10} m²/s for untreated (control) samples, whereas those pretreated with citric acid solution exhibited D_{eff} values ranging from 1.753×10^{-10} to 3.797×10^{-10} m²/s.

The corresponding activation energy values were calculated as 31.66 kJ/mol for the control group and 32.70 kJ/mol for the pretreated samples. In the case of infrared drying, the effective moisture diffusivity of celery samples varied between 2.746×10^{-10} and 4.987×10^{-10} m²/s for the control group. The activation energy required for moisture diffusion under infrared drying conditions was calculated as 2.99 kW/kg. In addition, color parameters were evaluated to assess the impact of drying methods on visual quality. Instrumental color measurements based on the CIELAB color space (L*, a*, b*) revealed noticeable changes depending on the drying technique and pretreatment.

Keywords: Celeriac, drying techniques, drying kinetics, mathematical modeling

INTRODUCTION

Celery (*Apium graveolens* L.), high in moisture content (approximately 88%), is a root vegetable with high nutritional value and functional properties. Celery, with its rich content, can positively affect health in many ways by preventing inflammation, regulating blood pressure, supporting digestion, etc. However, its high water activity significantly limits its shelf life, necessitating the use of preservation techniques such as drying [1, 2].

Drying serves as a traditional technique that reduces moisture content in agricultural goods, helping to prevent deterioration and support long-term storage. It significantly reduces the moisture content of food materials, thereby inhibiting microbial growth, enzymatic activity, and other deteriorative reactions [3-5]. Moreover, the reduction in weight and volume resulting from water removal leads to decreased transportation and storage costs. The high water content and water activity inherent in many fresh agricultural products accelerate spoilage processes; therefore, drying serves as an essential technique to enhance product stability, ensure microbiological safety, and maintain quality during storage and distribution.

Drying techniques have significant effects on the drying process, energy consumption and final product quality of food products. Depending on the applied method, parameters such as drying speed, moisture diffusion, color change, nutrient loss and structural integrity may vary. Therefore, the selection of the appropriate drying technique is critical to maximize process efficiency and energy savings while maintaining the desired quality characteristics of the product [6-8].

The present study investigates the impact of various drying methods on the drying characteristics of celeriac, focusing on parameters like drying rate, moisture loss, and time efficiency and color change. Understanding these kinetic aspects is essential for optimizing drying processes and improving the quality of the final product.

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EXPERIMENTAL

Materials and methods

High-quality fresh celery was sourced from a local vendor in Istanbul, Türkiye. The stalks were thoroughly cleaned and then diced into uniform cubes with an average thickness of approximately 6 ± 0.5 mm. The initial moisture content was measured as 9.43 kg of water per kg of dry matter (d.b.). The prepared samples were categorized into two distinct groups: one batch underwent pretreatment with a 1% (w/v) citric acid (CA) solution, while the second group remained untreated and served as the control. Drying of both sample groups was performed using two different methods: a convective cabinet dryer (APV&PASILAC Limited of Carlisle, UK) and an infrared (IR) dryer (Snijders Tilburg, Holland). In the cabinet drying process, samples were dried at constant temperatures of 55, 65, and 75 °C, whereas in the IR drying process, infrared power levels of 62, 74, 88, and 104 W were applied. During the drying process, the mass of the celery samples was recorded at 15-min intervals. Drying was terminated when the moisture content of the samples reached 0.10 ± 0.02 kg water/kg dry matter (d.b.).

Mathematical modeling and data analysis

To characterize the drying behavior, eight different semi-theoretical models were selected (Table 1). The mathematical expressions utilized for modeling and analyzing the drying data are listed in Table 2. In these models, MR refers to the moisture ratio, M indicates the moisture content (kg water/kg dry matter), W represents the total weight of the sample (kg), and Wd denotes the dry matter weight (kg). The variable t stands for drying duration in min. M_t and M_e correspond to the moisture content at time t and the equilibrium moisture content, respectively, both expressed in kg water/kg dry matter. Since M_e is relatively insignificant compared to the initial (M_0) and time-dependent (M_t) moisture contents, it is commonly omitted, simplifying the moisture ratio (MR) to the ratio M_t/M_0 [9].

Table 1. Mathematical models for kinetic investigation

Model name	Model	Ref.
Wang & Singh	$MR = 1 + at + bt^2$	[7]
Lewis	$MR = \exp(-kt)$	[10]
Henderson & Pabis	$MR = a\exp(-kt)$	[11]
Logarithmic	$MR = a\exp(-kt) + c$	[12]
Page	$MR = a\exp(-kt^n)$	[13]
Midilli & Kucuk	$MR = a\exp(-kt^n) + bt$	[14]
Vega-Lemus	$MR = (a + bt)^2$	[15]
Vega-Galvez	$MR = \exp(n + kt)$	[15]

Statistica 8.0.550 (StatSoft Inc., USA) software package was used to evaluate experimental data. To estimate model parameters a non-linear regression procedure based on the Levenberg-Marquardt algorithm was used. The adequacy of the experimental data fitting to various models was assessed using statistical parameters including the coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE). In this context, MRexp,i and MRpre,i represent the experimental and model-predicted dimensionless moisture ratios, respectively; N denotes the number of observations, and z is the number of model parameters. A good agreement between the model and experimental data is indicated by a higher R^2 value along with lower χ^2 and RMSE values [16]. The effective moisture diffusivity of dried celery can be estimated by applying Fick's second law of diffusion.

The relationship between effective moisture diffusivity and temperature is typically characterized using the Arrhenius-type equation, where D_0 represents the pre-exponential factor (m²/s), E_a is the activation energy (kJ/mol), R is the universal gas constant [kJ/(mol·K)], and T denotes temperature (°C). However, in the context of this study, temperature was not directly measurable under infrared drying conditions. Therefore, a modified version of the Arrhenius equation was employed to estimate activation energy, expressing the dependence of effective diffusivity on the ratio of infrared power input (p, W) to sample mass (m, kg) [7].

Table 2. Equations for data analysis

$M = \frac{W - W_d}{W_d}$	$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{N}(\overline{MR}_{pre} - MR_{exp,i})^2}$
$MR = \frac{M_t - M_e}{M_0 - M_e}$	
$MR = \frac{8}{\pi^2}\exp(-\frac{\pi^2 D_{eff} t}{4L^2})$	$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N - z}$
$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\right)t$	$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2\right]^{1/2}$
$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M$	$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T + 273.15)}\right)$
$K = \left(\frac{\pi^2 D_{eff}}{4L^2}\right)$	$D_{eff} = D_0 \exp\left(-\frac{E_a m}{p}\right)$

Color analysis

Color evaluation was conducted using a colorimeter (Konica Minolta CR-400, Japan). The analysis was based on the CIE (Commission Internationale de l'Éclairage) color space system, which defines color in three components: lightness (L*), ranging from 0 (pure black) to 100 (pure white); a* value, representing the red-green spectrum (from −60 for green to +60 for red); and b* value, indicating the blue-yellow scale (from −60 for blue to +60 for yellow). For each sample, measurements were recorded at three different surface locations, and the procedure was repeated six times to ensure accuracy and reproducibility of the average values.

DISCUSSION

Analysis of drying curves

Figure 1 illustrates the influence of air temperature and IR power on the moisture content and drying time of celery samples. The figure depicts moisture content variations as a function of drying time at temperatures of 55, 65, and 75°C, combined with IR power levels of 62, 74, 88, and 104 W. It is evident that moisture content consistently decreases throughout the drying process. Pretreatment was found to have no significant effect on drying time, as samples subjected to pretreatment exhibited drying durations comparable to the control group. Specifically, the drying times required to reduce the moisture content of pretreated samples were 210, 195, and 135 min, respectively, while the corresponding drying times for the control samples were 210, 195, and 150 min at the same temperatures.

The moisture content of the samples showed a clear decreasing trend over time, with a more rapid decline observed under higher infrared power levels. This can be attributed to the increased thermal input, which raised the sample temperature and accelerated moisture migration. Accordingly, the drying time required to reach the final moisture content decreased with increasing infrared power, with values ranging from 165 to 90 min depending on the applied power levels (62 to 104 W). As expected, higher infrared intensities resulted in greater heat absorption, leading to elevated product temperatures, enhanced mass transfer driving forces, and, consequently, faster drying rates and shorter drying times [7-10]. As highlighted in Fig. 1, the drying process typically followed two distinct phases: an initial warming-up stage under non-isothermal conditions, characterized by a rapid temperature increase, followed by a falling-rate period. This latter phase is associated with increasing internal resistance to both heat and mass transfer as the moisture content diminishes. These findings are consistent with established drying behavior of biological materials, where rapid initial moisture loss—mainly due to surface evaporation—is followed by slower diffusion-limited transport. Similar observations have been reported in prior studies on drying various agricultural products [11-14].

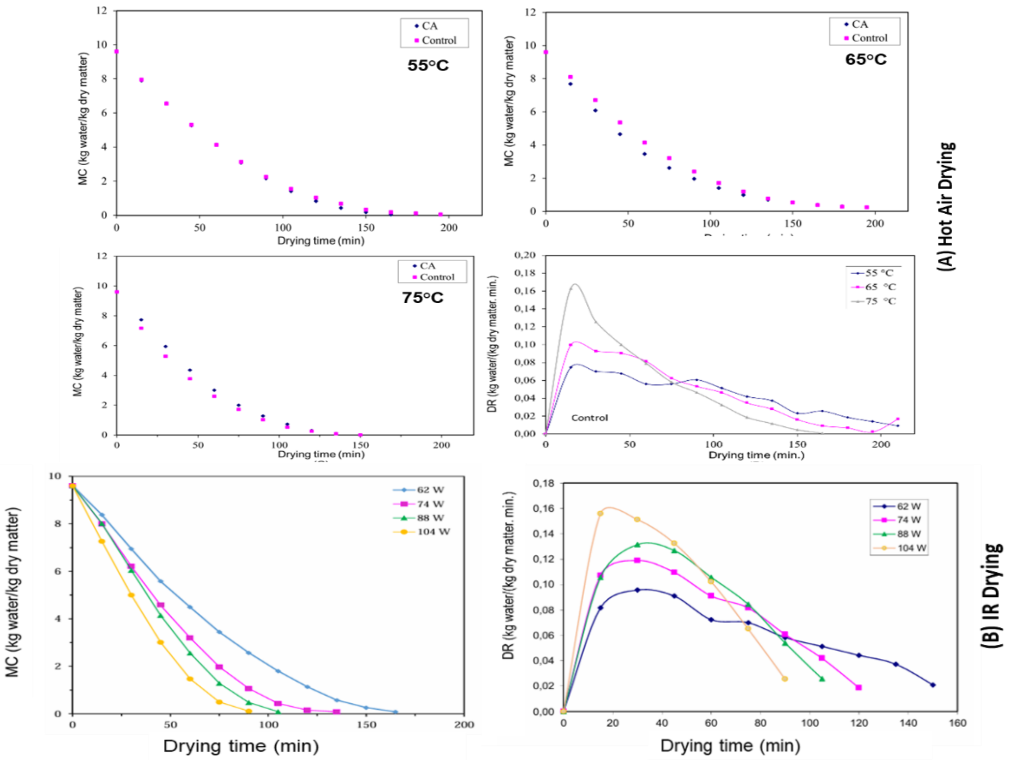


Figure 1. (A) Pretreatment effect on the moisture contents, and drying rate *versus* drying time for control sample, (B) Drying curves and drying rates of celery at different infrared powers

Evaluation of models

Model selection was primarily guided by achieving the highest R^2 along with the lowest χ^2 and RMSE values. As shown in Table 3, at 55 °C, the Wang & Singh model exhibited the strongest agreement with the observed data, reflected by an R^2 of 0.9993, a χ^2 of 0.000074, and an RMSE of 0.028052. However, for higher temperatures (65 °C and 75 °C), the Midilli & Küçük model outperformed the others, attaining R^2 values in the range of 0.9995–0.9998, χ^2 values between 0.000055 and 0.000024, and RMSE values from 0.019765 to 0.010345. Across varying infrared power levels, the Midilli & Küçük model consistently emerged as the most accurate, with R^2 values spanning from 0.9990 to 0.9996, χ^2 ranging from 0.000062 to 0.000194, and RMSE values lying between 0.016719 and 0.028563.

Effective moisture diffusivity and activation energy

The effective moisture diffusivity (D_{eff}) values for celery slices during drying at air temperatures between 55°C and 75°C ranged from 1.701×10^{-10} to 3.317×10^{-10} m²/s for pretreated samples and from 1.753×10^{-10} to 3.797×10^{-10} m²/s for control samples. An increasing trend in D_{eff} values was observed with rising air temperature, with the highest diffusivity recorded at 75°C and the lowest at 55°C. These results fall within the commonly reported range of 10^{-12} to 10^{-8} m²/s for drying of food materials, and show good agreement with previously published values for celery slices [15]. Similarly, the effective moisture diffusivity values for samples subjected to IR drying were determined at power levels of 62, 74, 88, and 104 W. The D_{eff} values ranged from 2.746×10^{-10} to 4.987×10^{-10} m²/s, indicating a positive correlation between IR power and moisture diffusivity. Comparing the two drying methods, it is evident that both higher air temperatures and increased IR power levels enhance moisture diffusivity in celery slices (Figure 2). However, IR drying at higher power levels yields somewhat greater D_{eff} values compared to hot air drying at equivalent temperatures, suggesting that IR drying may accelerate moisture transport more effectively during drying. The activation energy values were found to be 32.70 kJ/mol and 31.66 kJ/mol for pretreated and control samples during hot air drying, respectively, and 2.99 kW/kg for control samples during IR drying. The E_a values lie within the general range of 12.7–110 kJ/mol for food materials [16, 17].

Color evaluation

Color analysis of celery samples dried using two different drying techniques revealed that the L* parameter decreased with increasing drying temperature and IR power, indicating a darkening of the color. Specifically, L* values ranged from 70.75 to 65.05 in the cabinet dryer and from 64.72 to 53.16 in the IR dryer. The a* parameter increased with rising drying temperature (from −0.80 to 1.71) and IR power level (from 0.73 to 5.52), reflecting an increase in redness. Furthermore, pretreated samples exhibited color parameters closer to those of fresh samples compared to control samples across all temperature levels.

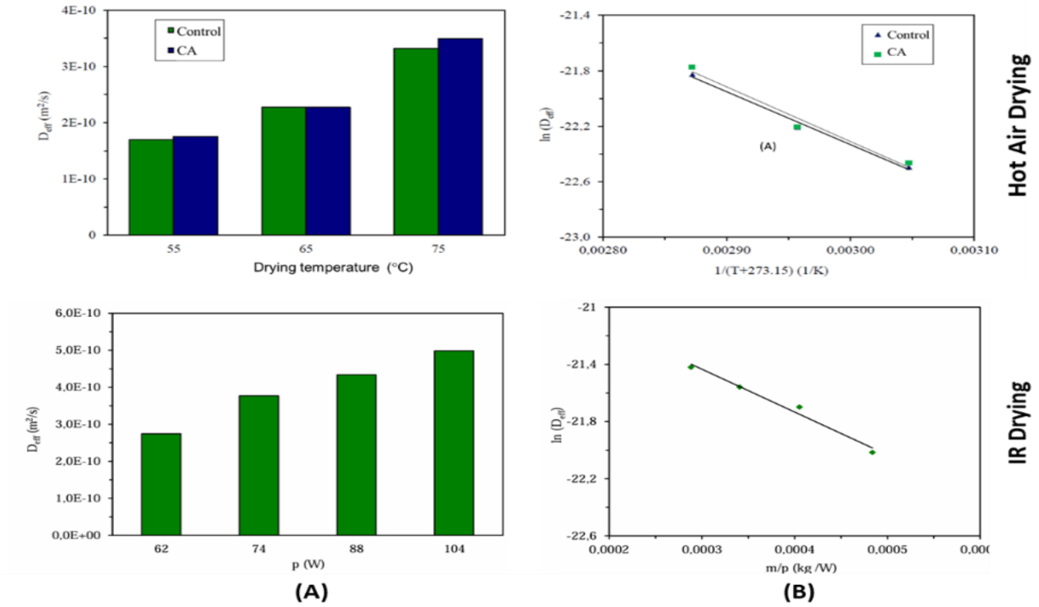
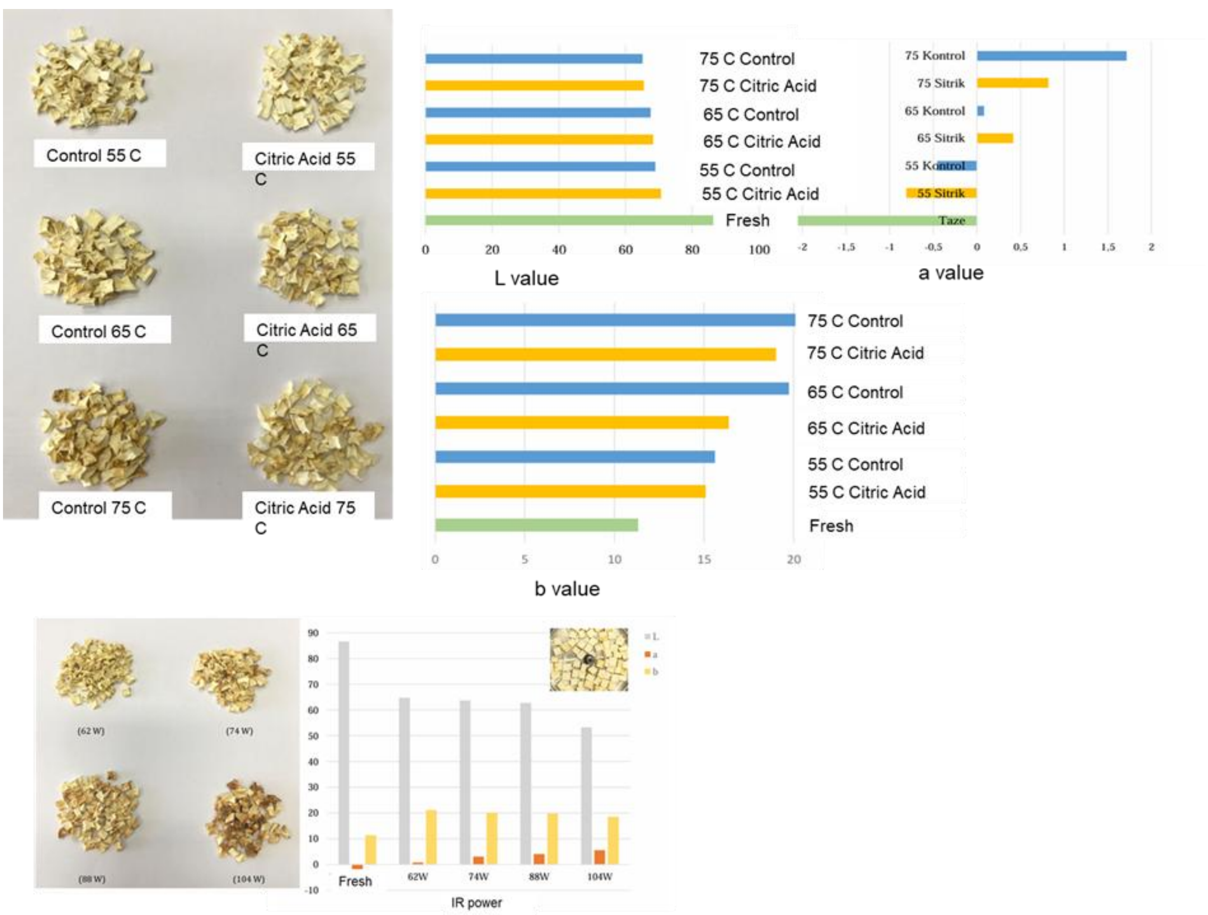


Figure 2. (A) Effective moisture diffusivity as affected by air temperature and IR power. (B) Arrhenius relationship between diffusivity and inverse absolute temperature (1/T) with m/p.

Table 3. Statistical parameters of models for different temperatures and infrared powers

MODELS			Lewis	Henderson & Pabis	Log.	Page	Midilli & Kucuk	Wang & Singh	Vega-Lemus	Vega-Galvez
Hot air	55 °C	R^2	0.9804	0.9855	0.9964	0.9984	0.9992	0.9993	0.9980	0.9855
		χ^2	0.002003	0.001578	0.000412	0.000165	0.000097	0.000074	0.000208	0.001578
		RMSE	0.167481	0.144327	0.069052	0.041601	0.029875	0.028052	0.047162	0.144328
	65 °C	R^2	0.9851	0.9888	0.9961	0.9993	0.9995	0.9981	0.9976	0.9888
		χ^2	0.001576	0.001272	0.000475	0.000070	0.000055	0.000215	0.000272	0.001272
		RMSE	0.132185	0.117040	0.065431	0.022864	0.019765	0.041112	0.050831	0.117040
	75 °C	R^2	0.9800	0.9838	0.9978	0.9986	0.9998	0.9996	0.9992	0.9838
		χ^2	0.002366	0.002159	0.000335	0.000181	0.000024	0.000051	0.000100	0.002159
		RMSE	0.126918	0.121613	0.043699	0.030588	0.010345	0.017603	0.024710	0.121613
IR	62 W	R^2	0.9671	0.9744	0.9977	0.9965	0.9996	0.9991	0.9993	0.9744
		χ^2	0.003810	0.003256	0.000313	0.000437	0.000062	0.000114	0.000088	0.003256
		RMSE	0.177461	0.162827	0.045495	0.058555	0.018325	0.023372	0.022232	0.162827
	74 W	R^2	0.9641	0.9708	0.9937	0.9975	0.9990	0.9975	0.9983	0.9708
		χ^2	0.004599	0.004205	0.001023	0.000352	0.000182	0.000358	0.000239	0.004205
		RMSE	0.181086	0.173649	0.074210	0.046037	0.028563	0.042915	0.038208	0.173648
	88 W	R^2	0.9500	0.9587	0.9936	0.9977	0.9996	0.9946	0.9943	0.9587
		χ^2	0.006866	0.006614	0.001216	0.000354	0.000080	0.000862	0.000914	0.006614
		RMSE	0.188368	0.185113	0.070901	0.037812	0.016719	0.058113	0.066087	0.185113
	104 W	R^2	0.9665	0.9707	0.9958	0.9973	0.9993	0.9982	0.9983	0.9707
		χ^2	0.004685	0.004915	0.000868	0.000444	0.000194	0.000299	0.000281	0.031880
		RMSE	0.143835	0.147733	0.056186	0.038988	0.023007	0.033338	0.004915	0.147729

Figure 3. Visual appearance and color parameter changes of celery dried by two different drying techniques



CONCLUSION

Celery, a nutrient-rich vegetable, was dried using hot air cabinet drying and IR drying techniques, and the drying behavior was examined. In hot air drying, increasing the temperature led to faster drying rates and shorter drying times for both pretreated and control samples. It was observed that the citric acid solution, applied as a pretreatment, did not have a significant effect on the total drying time and drying speeds for all temperature values. Diffusion coefficients and activation energies were slightly higher in pretreated samples compared to controls. For IR drying, raising the drying power similarly increased drying speed and reduced drying time, with diffusion coefficients higher than those in hot air drying and significantly lower activation energy. These findings suggest that IR drying is more effective and energy-efficient for celery than hot air drying.

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