



Original research

## Effects of combined drying method (osmotic-hot air) on the structural, color, and kinetic properties of apple cubes

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### ABSTRACT

In this study, the effects of combined drying method (Osmotic-Hot Air) on the structural, color, and kinetic properties of apple cuboids were investigated. Experiments were conducted using Box-Behnken design at three levels of drying temperature (60, 70, and 80 °C), three slice thicknesses (5, 10, and 15 mm), and three sucrose osmotic solution (40, 50, and 60%). Results showed that the overall effective diffusion coefficient of the tested samples varied between from  $4.36 \times 10^{-9}$  to  $1.46 \times 10^{-7}$  m<sup>2</sup>/s. The activation energy of samples ranged from 20.01 to 33.94 kJ/mol, increasing with slice thickness and sucrose osmotic solution. Among eight investigated models, the Midilli model demonstrated the best fit with experimental data, showing a coefficient of determination above 0.99. The browning index of samples varied between 140.54 to 140.83, with increases in slice thickness and drying temperature leading to higher browning indices, while increasing sucrose concentration from 40% to 60% resulted in decreased browning index. Analysis of Gray Level Co-occurrence Matrix (GLCM) parameters revealed that temperature increase led to higher energy, correlation, and homogeneity while reducing entropy. Conversely, increasing sample thickness resulted in decreased energy and correlation while increasing homogeneity and entropy. PLS regression analysis further confirmed the significance of drying temperature on GLCM parameters.

Keywords: Apple; Drying kinetics; Hot air; Osmotic dehydration.

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## 1. Introduction

Apple (*Malus domestica*) is one of the most popular and commonly consumed fruits globally, valued for its significant nutritional benefits and health-promoting properties due to its high content of phenolic compounds (e.g., flavonoids), and dietary fiber (especially pectin) (Patocka, et al., 2020). Research from various studies reveals that consuming apples regularly correlates with a lower incidence of cardiovascular ailments, type 2 diabetes, and specific forms of cancer (Hyson, 2011). However, apples are highly perishable due to their high moisture content (approximately 85%) rapidly losing quality without proper storage. Furthermore, the

seasonal nature of apple production necessitates effective preservation methods for continuous availability (Yang et al., 2024).

Drying is one of the oldest and most efficient food preservation methods, preventing microbial growth and undesirable biochemical reactions by reducing water activity. Hot air drying is the most common industrial drying method, widely utilized due to its ease of process control and relatively low operating costs. However, this method can lead to undesirable changes in product quality. Drying temperature is one of the most critical process parameters affecting drying rate and final product quality. By optimizing drying temperature, it is possible to enhance drying efficiency while minimizing quality deterioration such as browning and texture loss (Asrate & Ali, 2025).

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Osmotic dehydration, as an effective pretreatment, can mitigate many problems associated with hot air drying. In this process, the product is immersed in a hypertonic solution (typically sucrose, glucose, or salt) resulting in water removal from the product tissue and simultaneous solute uptake (Krokida et al., 2000). This phenomenon occurs due to the osmotic pressure gradient between the solution and the product. The osmotic solution concentration is one of the most important parameters affecting mass transfer rates and final product quality. Slice thickness is another key parameter influencing drying kinetics and final product uniformity.

Recent advances highlight that pretreatment strategies and process optimization critically influence the drying performance and quality of dried apples. Cichowska-Bogusz et al. (2020) found that adjusting osmotic dehydration conditions affects both drying kinetics and color retention. Wojtyś et al. (2025) showed that ultrasound-assisted osmotic dehydration improves water removal and preserves antioxidants. Jin et al. (2025) reported that optimized osmotic dehydration yields favorable microstructural and physicochemical changes, enhancing texture and reducing quality loss. Jia et al. (2024) applied advanced modeling to predict moisture and color changes during hot air drying, emphasizing precise process control. Salehi et al. (2022) also confirmed that ultrasound-assisted osmotic dehydration boosts dehydration rates and efficiency, though higher sucrose concentrations may lower rehydration capacity.

Slice thickness influences internal resistance to moisture transfer, with thicker slices generally drying more slowly. Mandala et al. (2005) reported that glucose-treated apple slices showed greater initial moisture loss, whereas sucrose-treated slices had slower rates due to crystallization. Osmotic pretreatment can also prevent browning, preserve appearance, and enhance rehydration properties when temperature and solution concentration are optimized (Krokida et al., 2000; Sereno et al., 2001). Moreover, such pretreatment can reduce energy consumption in drying processes (Torreggiani, 1993).

Moisture content evaluation over time is an important indicator for analyzing the drying process and comparing food materials' drying behavior. Drying rate, as a function of time or moisture content, aids in better understanding drying characteristics, and moisture diffusion can be estimated under specific conditions. Drying kinetics modeling, providing relationships between time and moisture variables, is an appropriate method for controlling drying conditions (Inyang et al., 2018). This modeling approach helps optimize drying parameters to achieve desired product quality and energy efficiency (Adnoui et al. 2023).

Color is a key quality attribute of dried products, influencing consumer acceptance. Its changes during drying arise from browning reactions, pigment degradation, and structural alterations (DeMan et al., 1999). Microstructure also governs functional and textural properties, as higher porosity enhances moisture removal, while denser structures impede it (Arnold & Gramza-Michałowska, 2022).

Despite extensive research on fruit drying, the comprehensive investigation of the interactive effects of slice thickness, sucrose osmotic solution, and drying temperature on drying kinetics and quality attributes of apple slices remains limited.

Therefore, this study aims to examine the effects of slice thickness (0.5, 1, and 1.5 cm) sucrose osmotic solution (40, 50, and 60%) and drying temperature (60, 70, and 80 °C) on drying kinetics, color changes, and structural properties of apple slices to optimize combined osmotic-hot air drying for enhanced quality.

## 2. Materials and Methods

### 2.1. Sample preparation

Apple samples, consisting of yellow apples (*Malus domestica*) purchased from the local market in Mashhad, Iran, were stored at 4 °C with 40% relative humidity until the initiation of experiments. Prior to each experiment, the required samples were washed, and surface moisture was removed using absorbent paper (Ahmad et al., 2021). The apples were then peeled and cut into cubic pieces measuring 20 × 20 mm with varying thicknesses of 5, 10, and 15 mm (Table 1). The initial moisture content of the apple samples was determined prior to the experiments and was found to be 73% (wet basis).

Table 1. Independent variable levels in Box-Behnken design for combined (osmotic-hot air) drying process of apple cuboids.

Sample codes	Drying temperature (°C)	Thickness (mm)	Sucrose osmotic solution (%)
1	70	15	60
2	70	10	50
3	70	10	50
4	70	10	50
5	60	15	50
6	80	15	50
7	60	10	40
8	70	5	40
9	60	10	60
10	70	10	50
11	70	10	50
12	80	10	40
13	80	10	60
14	70	15	40
15	80	5	50
16	60	5	50
17	70	5	60

### 2.2. Osmotic dehydration

Sucrose osmotic solutions were prepared at concentrations of 40, 50, and 60% (Table 1). The solutions were maintained in a water bath at 40 °C, where apple samples were immersed for 120 minutes. After osmotic treatment, samples were rinsed with distilled water and then gently blotted with absorbent paper to remove excess surface water before drying (Rahman, 2020). Throughout the osmotic process, solution temperature was monitored using a thermometer to ensure temperature stability.

### 2.3. Experimental procedure

Apple samples were dried in a hot air dryer at temperatures of 60, 70, and 80 °C (Table 1) until reaching constant moisture content. The experiments were conducted at the Research Institute of Food Science and Technology (RIFST), Mashhad, Iran. Subsequently, samples were removed from the dryer for evaluation.

The experimental design was conducted using a Box-Behnken design (with 5 replicates at the central point) (Kashaninejad, Najaf Najafi & Shateri, 2021) for three variables at three levels, resulting in a total of 17 treatments (Table 1).

Table 2. Mathematical models applied for modeling the drying kinetics of combined (osmotic-hot air) dried apple cuboids.

NO	Model Name	Model Equation	Reference
1	Newton	$MR = \exp(-kt)$	(Lemus-Mondaca et al., 2009)
2	Page	$MR = \exp(-kt^n)$	(Sun et al., 2007)
3	Henderson and Pabis	$MR = a \exp(-kt)$	(Akgun & Doymaz, 2005)
4	Two- term	$MR = a \exp(-bt) + c \exp(-dt)$	(Zielinska & Markowski, 2010)
5	Logarithmic	$MR = a \exp(-kt) + c$	(Liu et al., 2009)
6	Approximation of diffusion	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$	(Menges & Ertekin, 2006)
7	Midilli	$MR = a \exp(-kt^n) + bt$	(Vega-Gálvez et al., 2012)
8	Weibull distribution	$MR = a - b \exp(-kt^n)$	(Babalís et al., 2006)

#### 2.4. Investigation of drying kinetics

For studying drying kinetics, samples were removed from the dryer at predetermined time intervals and weighed using a digital balance (AND.EK-300i model, Japan) with  $\pm 0.01$ g precision. This process continued until the samples reached a constant weight. For modeling the drying process, the moisture ratio (MR) was calculated using the initial moisture content (MC<sub>i</sub>), equilibrium moisture content (MC<sub>e</sub>), and moisture content at any given time (MC) according to Eq. (1) (Ertekin & Yaldiz, 2004; Igwe & Igwe, 2023).

$$MR = \frac{MC - MC_e}{MC_i - MC_e} \quad (1)$$

For apple samples in this study, MC<sub>e</sub> was calculated to be approximately 4% (dry basis).

#### 2.5. Determination of effective moisture diffusivity

The effective moisture diffusivity was calculated based on Fick's second law using Eq. (2) (Tepe & Tepe, 2020).

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

Where MR represents the moisture ratio, D<sub>eff</sub> is the effective moisture diffusivity (m<sup>2</sup>/s), L is the half-thickness of the sample (m), t represents the drying time (s), and n= 1, 2, 3, ... is a positive integer. Through solving Fick's equation, moisture diffusion for an infinite slab can be calculated using Eq. (3) (Falade & Solademi, 2010).

$$\ln(MR) = \ln\left(\frac{8}{\mu^2}\right) - \left(\frac{\mu^2 D_{eff} t}{4L^2}\right) \quad (3)$$

By plotting Ln (MR) against drying time, a straight line with slope K (Eq. (4)) is obtained, which is utilized to calculate the effective diffusion coefficient.

$$K = \frac{\mu^2 D_{eff}}{4L^2} \quad (4)$$

#### 2.6. Activation energy calculation

The activation energy was calculated using the Arrhenius equation, which explains the correlation between temperature and effective diffusivity coefficient (Eq. (5)) (Lopez et al., 2000).

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (5)$$

Where D<sub>0</sub> is the Arrhenius factor (m<sup>2</sup>/s), E<sub>a</sub> indicates the activation energy for moisture diffusion (kJ/mol), R is the universal gas constant (kJ/k.mol), and T represents the absolute temperature (K). The activation energy can be obtained by plotting LnD<sub>eff</sub> against the reciprocal of temperature (1/T).

#### 2.7. Fitting of drying curves and model selection

Table 2 presents various empirical models for drying agricultural products. Following the completion of the drying process, these models were employed to fit the experimental data by determining MR to analyze moisture content variations during the drying period. Non-linear regression analysis was performed using MATLAB 2016 software to fit the models to the experimental data. The goodness of fit was assessed using statistical parameters such as coefficient of determination (R<sup>2</sup>), adjusted coefficient of determination (R<sup>2</sup><sub>adj</sub>), root mean square error (RMSE), and sum of square error (SSE). The best model was chosen according to the highest values of R<sup>2</sup> and R<sup>2</sup><sub>adj</sub> along with the lowest values of RMSE and SSE (Kashaninejad, Razavi, & Salahi, 2021).

#### 2.8. Image feature extraction of samples

The imaging equipment consisted of a dark chamber (to prevent imaging fluctuations and light reflection) with illumination controlled by fluorescent lamps. Images were captured using a Samsung SM-N960U1 camera connected to a computer. The camera was mounted on a fixed stand at a distance of 10 cm parallel to the samples. All images were captured in JPG format with a resolution of 4032×3024 pixels in RGB color model. To eliminate unnecessary image sections and reduce image processing volume, initial crops of 500×500 pixels were obtained using Image J software (National Institute of Health, USA), which was also used for subsequent image analysis. The analysis began with thresholding in the grayscale channel at an intensity of  $95 \pm 5$ , followed by examination of image features including energy, correlation, and uniformity.

The CIE Lab\* color model was employed to determine the color parameters of samples, where:

- L\* represents lightness (0 for black to 100 for white)
- a\* indicates red (+60) to green (-60)
- b\* shows yellow (+60) to blue (-60)

The mean values of L\*, a\*, and b\* were measured for 15 samples in duplicate. Subsequently, the Browning Index (BI), which indicates the product's color change towards brown, was calculated using Eq. (6) (Pathare, et al., 2013).

$$BI = \frac{(100 - (X - 0.31))}{0.71} \quad (6)$$

where X is defined as:

$$X = \frac{a + 1.75L}{5.645L + a - 3.012b}$$

### 3. Results and Discussion

#### 3.1. Analysis of drying curves

Fig. 1 illustrates the drying curves of apple cuboid samples with thicknesses of 5, 10, and 15 millimeters, osmotically dehydrated at concentrations of 40, 50, and 60 percent, and dried at temperatures of 60, 70, and 80 °C. As observed in the figure, and consistent with the findings of Masztalerz et al. (2020) the drying process occurs in two distinct phases. The first phase proceeds at a nearly constant rate (0 to 30 minutes), while the second phase exhibits a falling rate (after 30-40 minutes).

During the first phase, as also observed by Krokida et al. (2000) the rate of moisture transfer from the interior to the surface approximately equals the surface evaporation rate due to the presence of free moisture on the sample surface. This results in a rapid and linear decrease in moisture content. These findings align with the results reported by Mandala et al. (2005) in their study on apple drying kinetics.

As time progresses and the critical moisture point is reached, the process enters the second phase, during which the drying rate gradually decreases. This reduction in drying rate is attributed to limitations in moisture transfer from the internal tissue to the surface (Kahraman et al., 2021).

As illustrated in Fig. 1, increasing the drying air temperature from 60 °C to 80 °C significantly accelerates the reduction of moisture ratio in apple cuboids. At 80 °C, the curve slope during the first phase is steeper, and the critical moisture point occurs earlier. This phenomenon can be attributed to the increased temperature gradient, resulting in enhanced heat and mass transfer rates. Samples dried at 60 °C required a longer time to reach equilibrium moisture content. The effect of drying temperature on process rate observed in this study aligns with findings reported by Azoubel et al. (2008) who similarly documented that temperature elevation significantly reduces drying time. At 80 °C, consistent with Torreggiani's (1993) findings, the curve slope in the initial phase is steeper, with an earlier occurrence of the critical moisture point. Analysis of sample thickness effects reveals that increasing the thickness from 5 to 15 mm significantly extends the drying time. Samples with 5 mm thickness reached the final moisture ratio considerably faster than the thicker samples, indicating a greater resistance to moisture transfer in thicker samples. These observations regarding thickness effects correspond with Mandala et al.'s (2005) results, which showed that increased thickness leads to substantially longer drying times. This phenomenon can be attributed to the extended moisture migration path in thicker samples.

The results of the evaluation of sucrose osmotic solution indicate that pretreatment with higher concentrations (70%) leads to a significant reduction in overall drying time, particularly evident during the constant rate period. Samples pretreated with 40% concentration required longer times to reach equilibrium moisture content. This phenomenon can be attributed to structural changes in the tissue and initial moisture reduction during osmotic dehydration. These findings align with Masztalerz et al.'s (2020) research, which

demonstrated that pretreatment with higher concentrations significantly reduces overall drying time.

#### 3.2. Effective diffusion coefficient and activation energy

The effective diffusion coefficient for all apple cuboid samples was calculated by plotting LnMR against drying time, fitting the linear curve with equation (4) and determining the slope. Results indicated a non-linear relationship between LnMR and time, suggesting that the effective diffusion coefficient varies with moisture content across all samples. The effective diffusion coefficient ranged from  $4.36 \times 10^{-9}$  to  $1.46 \times 10^{-7}$  m<sup>2</sup>/s. Analysis of variance revealed that the linear effects of temperature and thickness were significant at 99% confidence level, while the temperature-thickness interaction was significant at 95%. However, sucrose osmotic solution showed no significant effect on the effective diffusion coefficient.

Fig. 2 illustrates the influence of drying temperature and thickness on the effective diffusion coefficient of apple cuboid samples. Increasing drying temperature enhances the effective diffusion coefficient due to temperature's positive effect on reaction intensity and molecular kinetics. This finding corresponds with Krokida et al.'s (2003) study, which reported increased effective diffusion coefficients with temperature elevation from 30 °C to 70 °C. Although increased thickness results in slower drying rates, it leads to higher effective diffusion coefficients. Sereno et al. (2001) demonstrated that changes in food material pore structure influence diffusion coefficients, with higher porosity facilitating greater moisture mobility and higher effective diffusion coefficients.

Masztalerz et al. (2020) found that while the slope decreases with increased thickness during different drying stages, the effective diffusion coefficient increases. This can be explained by the longer moisture migration distance in thicker samples. Torreggiani (1993) confirmed that the L2 parameter in the effective diffusion coefficient equation plays a crucial role in increasing this coefficient at higher thicknesses. As noted by Mandala et al. (2005) a higher diffusion coefficient doesn't necessarily indicate faster drying rates or shorter drying times, as these parameters depend on multiple factors including sample quantity and thickness. Lewicki and Porzecka-Pawlak's (2005) microscopic studies showed that structural changes in apple tissue during osmotic dehydration don't significantly differ across various sucrose osmotic solutions, explaining the non-significant effect of solution concentration on the effective diffusion coefficient.

The activation energy of samples was calculated from the plot of Ln Deff versus the reciprocal of absolute temperature. Fig. 3 illustrates the variations in activation energy for apple cuboid drying as a function of sucrose osmotic solution and sample thickness. Based on the experimental results, the activation energy of the tested samples varied between 20.01 and 33.94 kJ/mol within the temperature range of 60-80 °C. As shown in the figure, activation energy increased with both increasing thickness and sucrose osmotic solution (Fig. 3).

Activation energy indicates the temperature sensitivity of a reaction or process. The observed increase in activation energy with increasing apple sample thickness demonstrates that samples with greater thickness exhibit enhanced sensitivity of effective diffusion coefficient to changes in drying temperature conditions compared to thinner samples. According to Krokida et al. (2003) as sample thickness increases, the moisture migration path from center to surface becomes longer. This phenomenon increases resistance to

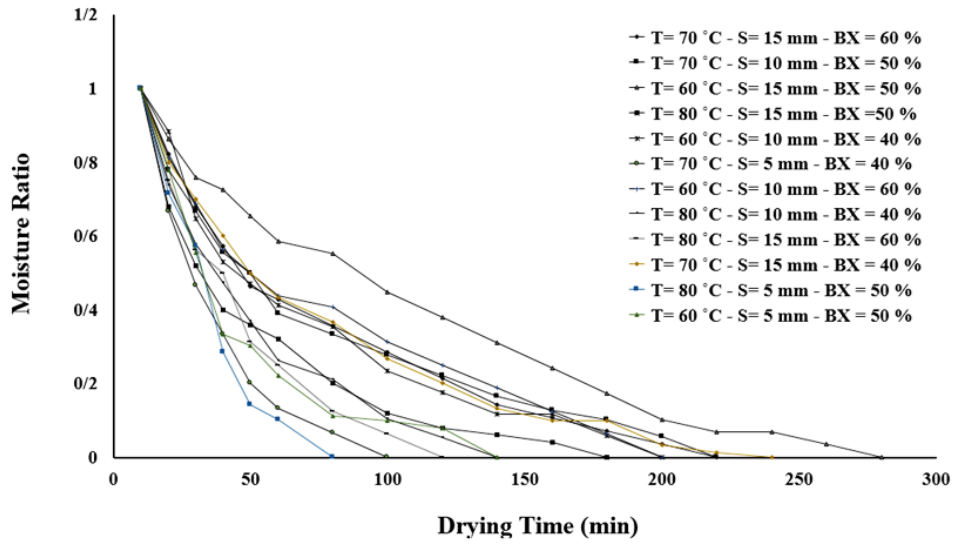


Fig. 1. Changes moisture ratio during the combined drying time (osmotic-hot air) of apple cuboids.

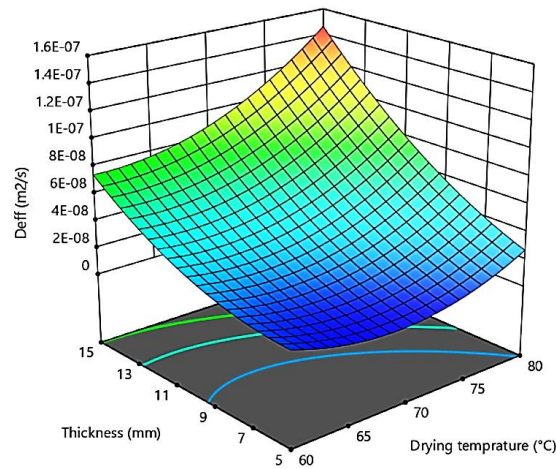


Fig. 2. The effect of drying temperature and thickness on the effective diffusivity of apple cuboid samples.

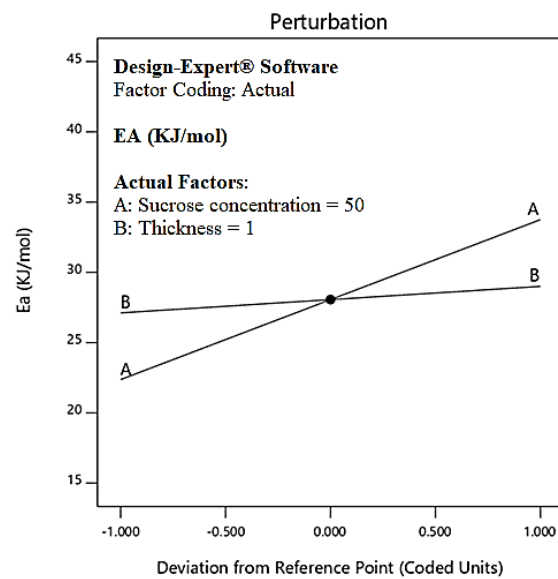


Fig. 3. Changes in activation energy for different osmotic concentrations and drying thicknesses of apple cuboids.

mass transfer, consequently requiring more energy to overcome this resistance.

Mandala et al. (2005) demonstrated that thicker samples contain higher moisture content, requiring greater activation energy for moisture evaporation. Torreggiani and Bertolo (2001) reported that higher sucrose osmotic solutions lead to increased accumulation of soluble solids on sample surfaces. This concentrated layer acts as a barrier to moisture removal, necessitating higher activation energy for moisture transfer through this layer. Lewicki et al. (2005) observed that increasing sucrose osmotic solution leads to more pronounced structural changes in cellular tissue. These modifications include cell shrinkage, alterations in cell wall structure, and accumulation of solid matter in intercellular spaces, which collectively result in increased resistance to moisture transfer and, consequently, higher activation energy. These microstructural changes significantly influence the mass transfer mechanisms during the subsequent drying process.

### 3.3. Drying process modeling and selection of the best model

The experimental drying data (moisture ratios (MR) versus time) were fitted to eight semi-empirical models (Table 2). The models were compared using four statistical criteria: coefficient of determination ( $R^2$ ), adjusted coefficient of determination ( $R^2_{adj}$ ), root mean square error (RMSE), and sum of square error (SSE). The optimal model was selected based on the highest values of  $R^2$  and  $R^2_{adj}$  combined with the lowest values of RMSE and SSE.

According to these statistical criteria, the Midilli model demonstrated the best fit to the experimental data across all drying conditions, including various drying temperatures, sucrose osmotic solutions, and sample thicknesses, with  $R^2$  and  $R^2_{adj}$  values exceeding 0.99. The constants for the Midilli model under different experimental conditions are presented in Table 3.

The Midilli model is one of the validated models in food drying kinetics that has been utilized in numerous studies. Chen and Mujumdar (2009) demonstrated in their research that this model, with its three parameters ( $k$ ,  $n$ , and  $a$ ) offers high flexibility in fitting experimental data. Inyang et al. (2018) reported that the  $k$  parameter, as the drying constant, indicates the overall process rate, while the  $n$  parameter, as the model power, describes the deviation from linear diffusion conditions. Xiao et al. (2009) found in their study that this model performs particularly well under osmotic pretreatment conditions, as it can account for the impact of structural changes caused by the osmosis process on drying kinetics. Erbay and Icier (2010) also confirmed that the Midilli model can accurately predict moisture content changes during drying time and performs effectively in different drying stages (constant and falling rate periods). Hany et al (2024) demonstrated that increasing infrared intensity accelerates the drying of apple slices, whereas greater slice thickness and higher air velocity tend to prolong the drying time. Their study identified the Midilli model as the best fit for describing drying behavior under varied conditions. Reported effective moisture diffusivity values ranged from  $2.59$  to  $9.07 \times 10^{-10}$   $m^2/s$ , while activation energy values varied between 19 and 30  $kJ/mol$ .

### 3.4. Color (Browning index)

The color of samples can be influenced by various factors, including drying temperature, drying time, enzymatic and non-enzymatic browning, moisture content, and surface moisture

(Dehghannya et al., 2018; Salahi et al., 2017). The results of this investigation showed that the browning index of the tested samples varied between 140.54 and 140.83. Among linear, interactive, and quadratic effects, the linear effects of thickness and sucrose osmotic solution, as well as the interaction effects of temperature-thickness, temperature-sucrose osmotic solution, and thickness-sucrose osmotic solution were significant at the 99% confidence level on the samples' browning index. Fig. 4 illustrates (a) the effect of drying temperature and apple slice thickness, and (b) the effect of drying temperature and sucrose osmotic solution on the browning index of the samples.

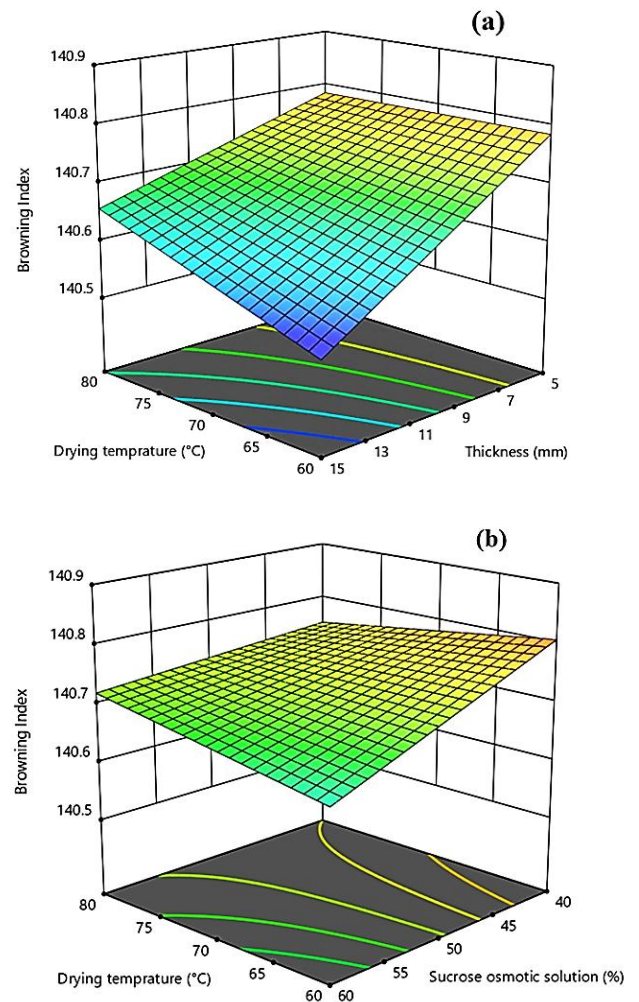


Fig. 4. (a) The effect of drying temperature and thickness of apple cuboids, and (b) the effect of drying temperature and sucrose osmotic solution on the browning index of the samples.

Fig. 4a demonstrates that at a constant sucrose osmotic solution (50%) increasing the drying temperature and decreasing sample thickness led to an increase in the browning index. This phenomenon can be attributed to enhanced polyphenol oxidase enzyme activity at higher temperatures (Fanta et al., 2013). Furthermore, in thinner samples, enzymatic browning is intensified due to a higher surface-to-volume ratio and increased oxygen exposure.

Table 3. Midilli model constants for different combined drying treatments (osmotic-hot air) of apple cuboids.

Sample codes	Drying temperature (°C)	Thickness (mm)	sucrose osmotic solution (%)	Midilli model					
				a	b	k	n	R <sup>2</sup>	RMSE
1	70	15	60	1.0123	0.00045	0.0078	1.2345	0.9989	0.0098
2	70	10	50	1.0234	0.00056	0.0089	1.2234	0.9992	0.0087
3	70	10	50	1.0345	0.00034	0.0056	1.3456	0.9995	0.0076
4	70	10	50	1.0156	0.00067	0.0098	1.1987	0.9987	0.0102
5	60	15	50	1.0234	0.00045	0.0067	1.2567	0.9989	0.0089
6	80	15	50	1.0345	0.00056	0.0089	1.2123	0.9992	0.0078
7	60	10	40	1.0123	0.00034	0.0065	1.2345	0.9990	0.0085
8	70	5	40	1.0456	0.00067	0.0078	1.2234	0.9988	0.0092
9	60	10	60	1.0234	0.00078	0.0092	1.1987	0.9985	0.0098
10	70	10	50	1.0345	0.00023	0.0054	1.3567	0.9996	0.0067
11	70	10	50	1.0123	0.00045	0.0076	1.2345	0.9991	0.0082
12	80	10	40	1.0456	0.00056	0.0065	1.2567	0.9989	0.0087
13	80	10	60	1.0234	0.00034	0.0078	1.2345	0.9990	0.0085
14	70	15	40	1.0345	0.00067	0.0067	1.2456	0.9988	0.0092
15	80	5	50	1.0123	0.00045	0.0089	1.2123	0.9989	0.0089
16	60	5	50	1.0456	0.00056	0.0076	1.2345	0.9991	0.0083
17	70	5	60	1.0234	0.00045	0.0082	1.2234	0.9990	0.0086

Examining the effect of drying temperature and sucrose osmotic solution at a constant thickness (10 mm) (Fig. 4b) increasing sucrose osmotic solution resulted in a decrease in the browning index of samples. Increasing drying temperature led to an increase in the browning index at high sucrose osmotic solutions, while causing a decrease at lower sucrose osmotic solutions. This phenomenon can be attributed to greater sugar penetration at higher osmotic concentrations, which inhibits polyphenol oxidase enzyme activity and reduces enzymatic browning (Martynenko & Janaszek, 2014). Additionally, increased sugar content reduces water activity, and sugars can act as a barrier against oxygen, thereby further reducing browning (Mandala et al., 2005).

The interaction effect between temperature and sucrose osmotic solution revealed that at high osmotic concentrations, increasing drying temperature leads to higher browning index values, whereas at low concentrations, temperature increases result in decreased browning index. At high osmotic concentrations, although greater sugar penetration provides initial protective effects against browning, higher drying temperatures can accelerate enzymatic activity. At low osmotic concentrations, enzymatic browning remains significant due to reduced sugar penetration. Under these conditions, temperature increases can reduce the overall time available for enzymatic reactions by accelerating the drying process (Moon et al., 2020).

### 3.5. Gray level co-occurrence matrix (GLCM)

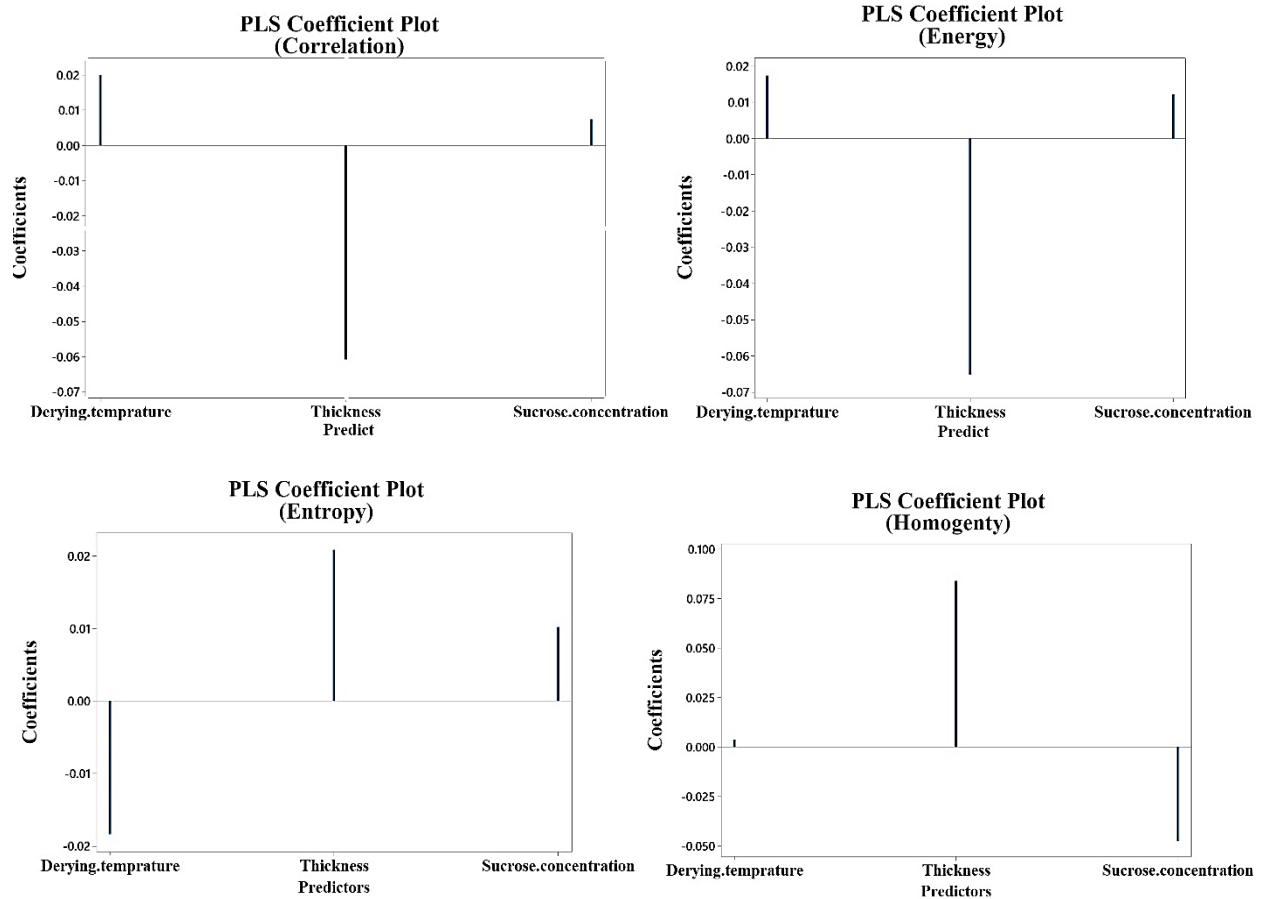
The results showed that energy, correlation, homogeneity, and entropy of the tested samples varied between 0.44-0.54,  $5.4 \times 10^{-3}$ - $6.2 \times 10^{-5}$ , 0.92-0.95, and 0.83-0.92, respectively. In this study, Partial Least Squares (PLS) regression was employed to evaluate the impact of independent variables (drying temperature, thickness, and sucrose osmotic solution) on textural parameters (energy, correlation, homogeneity, and entropy). To determine the importance coefficient and impact level of each independent variable on textural parameters, standardized coefficient plots are presented in Fig. 5. In these plots, coefficient values closer to or greater than one indicate greater importance of that variable. The importance coefficients in this method can be either positive or negative, indicating the direction and magnitude of each independent variable's effect on

dependent variables. A positive coefficient indicates that an increase in the independent variable results in an increase in the dependent variable, while a negative coefficient signifies that an increase in the independent variable leads to a decrease in the dependent variable.

As shown in Fig. 5a, drying temperature has a positive effect on energy, correlation, and homogeneity, while negatively affecting entropy. Sample thickness demonstrates negative effects on energy and correlation, but positive effects on homogeneity and entropy (Fig. 5b). Additionally, sucrose osmotic solution shows positive effects on energy, correlation, and entropy, while negatively impacting homogeneity (Fig. 5c).

PLS regression analysis revealed that drying temperature positively correlates with GLCM textural characteristics (energy, correlation, and homogeneity). In other words, increasing drying temperature leads to higher values of these parameters in dried samples. Mandala et al. (2005) attributed this phenomenon to faster moisture removal at higher temperatures, resulting in a more compact and uniform textural structure. Krokida et al. (2000) also found that higher temperatures accelerate cell wall collapse, leading to the formation of a more compact matrix and consequently increased energy, correlation, and homogeneity of the texture. Conversely, the negative relationship between drying temperature and entropy indicates the formation of a more organized structure and reduced disorder in the texture at higher temperatures, which aligns with the findings of Sharma et al. (2024).

Analysis of sample thickness effects showed that increased thickness negatively impacts energy and correlation. Azoubel et al. (2009) attributed this phenomenon to non-uniform drying patterns in thicker samples and the formation of more irregular structures. Conversely, the positive effect of thickness on homogeneity and entropy corresponds with Rastogi et al.'s (2002) findings, which demonstrated that greater thickness leads to more diverse structural changes. Regarding sucrose osmotic solution, results indicate positive effects of increased concentration on energy, correlation, and entropy, with a negative impact on homogeneity. Torreggiani and Bertolo (2001) attributed this phenomenon to enhanced sugar penetration and stronger structural changes at higher concentrations. Lewicki and Porzecka-Pawlak (2005) related the decrease in homogeneity to non-uniform solid distribution in the texture due to high sucrose osmotic solution.



**Fig. 5.** Importance coefficients estimated by PLS regression between independent variables and dependent variables of Gray Level Co-occurrence Matrix (GLCM) for different dried apple slice samples.

### 3.6. Numerical optimization

For the numerical optimization of the combined osmotic pretreatment and hot air drying conditions for apple slices, the optimal values of independent variables (drying temperature, slice thickness, and sucrose osmotic solution) were determined using Design Expert software based on the models obtained for each response. In this optimization, the effective moisture diffusivity and homogeneity were targeted for maximization, while the browning index was minimized. According to the results of the models and the desirability function approach, the optimal process point was identified as a drying temperature of 70 °C, a slice thickness of 15 mm, and a sucrose osmotic solution of 45% sucrose. These conditions led to the highest effective moisture diffusivity and textural homogeneity while keeping the browning index at its lowest value. The optimization outcomes align with previous studies reporting that moderate drying temperatures combined with intermediate osmotic solution concentrations can balance quality and efficiency in fruit dehydration (Yadav & Singh, 2014). The selection of 70 °C likely enhanced internal moisture diffusivity without causing excessive thermal degradation of color pigments or cellular collapse, while the 45% sucrose concentration may have provided sufficient osmotic driving force to remove water and maintain tissue

integrity. The 15 mm slice thickness appears to have favored structural uniformity during drying by reducing over-drying at the edges and preserving internal microstructure. Collectively, these findings underscore the importance of jointly considering heat transfer, mass transfer, and quality attributes in process optimization to meet industrial demands for high-quality dried fruit products.

## 4. Conclusion

The results of this study demonstrate that the complex interaction between slice thickness, sucrose osmotic solution, and drying temperature significantly influences the drying kinetics and final quality of apple slices. Higher drying temperatures increased the effective moisture diffusivity and accelerated dehydration, while thicker slices and higher osmotic concentrations raised activation energy. Browning index increased with both temperature and thickness, but decreased at higher sucrose concentrations. Texture analysis indicated more organized structures at higher temperatures and more irregularity in thicker samples. Process optimization identified 70 °C, 15 mm thickness, and 45% sucrose as optimal conditions, resulting in efficient drying, improved texture homogeneity, and minimized browning. Overall, this research

demonstrates that optimal control of process parameters can lead to the production of high-quality dried apple slices with reduced energy consumption. The combined method of osmotic dehydration and hot air drying, when optimized, presents an effective approach for preserving fruits like apples.

## Conflict of interest

The authors declare that there is no conflict of interest.

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