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Drying Apple Slices in a Rotating-Tray Convective Dryer: A Study on Dehydration Characteristics and Qualitative Attributes

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ABSTRACT

To improve quality attributes of the final dried product and execute a better management of the required energy, optimal process and technology it is essential to dry agri-food materials. This work is aimed at studying the dehydration characteristics and qualitative traits (color, shrinkage, rehydration ratio) of apple in a rotating-tray convective dryer with different operational variables. Furthermore, to model the dehydration curves, the usage of some well-known semi-theoretical models and artificial neural networks (ANNs) was evaluated. The drying experiments were conducted by applying the constant thickness of the samples (3 mm), different air temperatures (50–85 °C) and flow rates (1 and 2 m s^{-1}*) as well as three tray rotating speeds (0, 6 and 12 rpm). In addition to significant (*$P < 0.05$*) reduction caused by increasing the temperature and flow rate, the process duration was considerably decreased by the increment in the tray rotating speed. The moisture diffusion inside the slices (*$2.708 \times 10^{-9} - 8.337 \times 10^{-9}$ m^2 s^{-1}*) was facilitated by increasing the values of evaluated variables. The average values for the activation energy changed from 20.47 to 23.80 kJ* mol^{-1}*. In comparison with the thin layer models, artificial networks showed better performance in modeling the curves. Although drying parameters did not significantly affect the quality of studied properties, in general, higher drying air velocities and temperatures deteriorated the quality of the final products.*

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1. Introduction

Drying is one of the processes ubiquitously used in the manufacturing industry to reduce the moisture content of wet materials to a certain level for marketing, storage and/or further processing. It has remained as the

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most popular method to preserve agricultural and food products for many years [1, 2]. The moisture removal from moist materials is performed by vaporizing water in the product and therefore, the vaporization latent heat must be supplied. Furthermore, air stream is usually required to remove the vapor away from the product [3, 4]. Among the different dehydration systems commonly utilized in domestic and industrial scales, convective dryers have gained acceptance and been employed to dry biological products. During the convective drying, the internal water of the product is transferred to its surface by diffusion and then evaporated by the air stream [5].

The tray dryer is the most widely used convective dryer since it is simple and has economic design. The uniform distribution of airflow over the trays is the key factor which ensures the successful operation of the tray dryer and the uniform final moisture content of the dried products on the trays. The tray dryers are divided into two main groups including: 1) stationary tray and 2) moving tray. The stationary tray dryers are simpler wherein the trays are fixed in their positions. However, reaching the desirable quality of the final product is crucial since there is no assurance for the uniform distribution of the air stream over the trays and the consistent moisture content of the product at different tray positions. The problem also restricts the quantity of the product that could be loaded in the drying chamber. To overcome these shortcomings, the moving tray dryers have been designed and employed. The movement of trays inside the drying chamber could help to enhance the drying rate and result in more uniform distribution of drying air and a better quality of the final product.

Drying is usually a complex unit operation process in which two phenomena including heat and mass transfers occur simultaneously and lead to the moisture evaporation from the material. To predict drying kinetics, control the process to achieve a certain quality of the final product, design new drying systems, and optimize the existing system, the process simulation is an effective and practical solution [6]. Mathematical models have been used by several researchers to simulate the drying process. Semi-theoretical models are developed based on approximate theoretical equations and usually, taking into account some simplification assumptions. It has been widely reported the use of semi-theoretical models by researchers, such as Kasara et al. (2021) [7], Mbegbu et al. (2021) [8], and Erol (2022) [9], to describe the drying kinetics for different products. In the last decade, the artificial intelligence, with the ability to produce results without the need for prior assumptions in issues where the relationship between dependent and independent parameters is complex, has received much attention. Several studies have used artificial neural networks to simulate drying processes such as drying paddy in a hot air dryer [10] and the kinetics of drying garlic in the fluidized bed dryer [11].

In addition to great amounts of energy consumption, drying agricultural and food products could cause some changes in the quality parameters of the materials. There are several research works reported about the open literatures regarding the influence of the moisture removal process on the physical, mechanical and chemical properties of biological products. Some of the studies have been briefly introduced in Table 1.

Based on the open literatures reviewed, it was found that few researchers have studied the influence of the tray movement on the drying parameters for different products. Sarsilmaz et al. (2000) developed and evaluated a rotary column tray dryer for drying apricots. They found that, compared to an open sheet, the moisture removal rate was about twice in the rotating dryer. Also the rotation system produced uniform and high-quality dried apricots [15]. Santos-Sánchez et al. (2012) developed a rotating tray dryer and evaluated it for drying tomatos. They found that the tray rotation enhanced the drying rate and improved the product quality [16]. Therefore, considering the previous studies reported on the topic, the main objective of this research work was to evaluate the influence of the drying tray rotation on the dehydration behavior as well as some important properties of drying products. To this end, apple slices were selected as the case study and, for the better conclusion about the rotation influence, the experiments were conducted at different inlet air temperatures and velocities. The obtained data was analyzed to assess the drying time, determine the mass transfer characteristics and quality parameters of the samples. Furthermore, modeling the moisture removal curves was performed using thin layer mathematical models and ANN; and the more accurate method was determined.

Table 1

Some research works reported about the influence of the drying process on the quality parameters of biological products.

Product	Drying system	Studied properties	Reference
Peppermint leaves	Hot air dryer and microwave dryer	Chemical composition of essential oil	6
Banana puree	Refractance Window	Ascorbic acid retention, color, retention of total phenolic and flavonoid contents, and antioxidant capacity	12
Daucus carota L.	Hot air dryer	Color, carotenoid retention, and rehydration ratio	13
Persimmon slices	Hot air dryer	Ascorbic acid, browning index and rehydration ratio	14

2. Materials and methods

2.1. Fresh apples

Fresh apples (Golden Delicious variety) were provided from a fruit and vegetables marketplace in Karaj, Iran. According to the standard oven method described by Beigi (2016) [17], the average moisture content of the fresh apples was found to be approximately 5.25 $g_{water}/g_{dry\ matter}$.

2.2. Drying experiments

Prior to each drying experiment, to stabilize the samples temperature, a desirable amount of fresh apples was taken from the refrigerator (temperature of 4 °C) and placed in the lab environment (approximately 25 °C) for 1 h. After peeling and accuratly cutting them into 3 mm slices, about 750 g of the apples was distributed as monolayers on the drying trays.

The detailed information on the characteristics of the rotating tray convective dryer has been described by Ghasemkhani et al. (2016) [1]. Different sets of the air temperature (50, 65 and 80 °C), air velocity (1 and 2 m s^{-1}) and tray speed (0, 6, and 12 rpm) were selected to perform the drying experiments. Throughout the process, to determine the instantaneous moisture content ($g_{\text{ water}}/g_{\text{ dry matter}}$) of the drying apples, the continuous mass monitoring of the samples lot was carried out and the following equation was used [18]:

$$M = \left[\frac{(M_0+1)\times W}{W_0} - 1\right] \tag{1}$$

where W and W_0 are instantaneous and initial masses (g) of drying apples (g) respectively. M and M_0 are the instantaneous and the initial moisture contents ($g_{\text{ water}}/g_{\text{ dry matter}}$) of the slices respectively.

2.3. Modeling

To model the experimental moisture removal kinetics (in term of moisture ratio, MR), two widely used modeling techniques including mathematical models and ANNs were selected. In case of the thin-layer models, the six well-known semi-theoretical models were fitted to the the obtained moisture ratio data. For the Artificial neural network modeling and predicting, the procedure was designed and followed as explained below:

1- A multilayer perceptron (MLP) network with different hidden layers (one and two) and numbers of neurons was used and a Feed Forward Back Propagation (FFBP) learning rule was used. Three transfer functions including linear (Lin), hyperbolic tangent sigmoid (Tan) and logarithmic sigmoid (Log) were used, and, Levenberge-Marquardt (LM) was applied for training the network,

2- Based on the experiments, the temperature and flow rate of the inlet air, tray rotation speed and drying time were selected as the inputs and the moisture ratio was considered as the output of the network,

3- After shuffling, the experimental data was divided into training, validation and testing subsets allocating 70, 15 and 15 % of the data respectively (Omari et al., 2018),

4- To attain the best model, the trial and error technique was used to optimize the ANN configurations,

5- The network was trained by the frequent usage of a known input/output data set and the weight factors were adapted,

6- The network was tested by 1) using different arrangements of the training step inputs and making some modifications to enhance the system reliability, and 2) assaying the system performance through subjecting the network to new inputs with identified outputs, and

7- For evaluating the accuracy of each modeling technique, the coefficient of determination (R^2) and root mean square error (RMSE) were used [6]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(MR_{exp,i}-MR_{pre,i})^2}{\sum_{i=1}^{n}(MR_{exp,i}-\overline{MR})^2} \tag{2}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})^2\right]^{0.5} \tag{3}$$

where, exp, i and pre,i are the i-th experimental and predicted values respectively. n is the observations number.

2.4. Moisture diffusivity (D)

The moisture removal in biological materials is mainly controlled by diffusion, and drying the thin products is expressed by the one-dimensional diffusion based on Fick's law [19]. According to the transient diffusion law, the moisture transfer can be expressed in the following form [3]:

$$\frac{\partial M}{\partial t} = D\nabla^2 M \tag{4}$$

Considering some assumptions such as the uniform distribution of moisture, based on the solid geometry, an analytical solution has been represented for Eq. (4) by Crank (1975) [20]. For a slab, it is written as:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[\frac{-(2n+1)^2\pi^2 Dt}{L^2}\right] \quad (5)$$

Because of the lengthy process in the present study, the series (Eq. 5) was shortened to the first term and rewritten as follows:

$$\ln MR = \ln\frac{8}{\pi^2} - \left(\frac{\pi^2 Dt}{L^2}\right) \quad (6)$$

By plotting the ln(MR) against time (t), and using the line slope (S), the moisture diffusivity was computed using the following equation:

$$D = -\frac{L^2}{\pi^2} \times S \quad (7)$$

In Eq. (7), D is the moisture diffusivity ($m^2\ s^{-1}$) and L is the thickness of samples (m).

2.5. Activation energy

The activation energy (E_a, kJ mol^{-1}) was computed by relating the diffusivity with the absolute temperature (T_{abs}, K) and as follows [6]:

$$\ln(D) = \ln(D_0) - \frac{E_a}{R}\left(\frac{1}{T_{abs}}\right) \quad (8)$$

where, D_0 is the diffusivity constant ($m^2\ s^{-1}$) and R is the universal gas constant.

Therefore, the ln(D) was plotted versus $1/T_{abs}$ and the obtained straight slope ($\acute{S}$) was used:

$$E_a = R \times \acute{S} \quad (9)$$

2.6. Assessment of the surface color of samples

The surface color of the dried and wet slices was measured in the CIE Lab space by using a computer vision system. The images from the randomly selected samples were provided by using a CCD color camera (Canon G9 digital color camera, Tokyo, Japan) with remote capturing capability, converted to binary images by using the image processing toolbox in MATLAB 7.10 software (MathWorks, Inc., Natick, MA) and analyzed. The total color difference (ΔE) was determined as follows:

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (10)$$

2.7. Shrinkage

To determine the shrinkage of the apple slices, the volumes of fresh and dried apple slices were determined using the standard toluene displacement method and Eq. (11) was used:

$$\text{Shrinkage} = \left(\frac{V_f - V_d}{V_f}\right) \times 100 \quad (11)$$

In Eq. (11), V_f and V_d represent the volumes (cm^3) of fresh and dried samples respectively.

2.8. Rehydration ratio

The rehydration ratio of the dried apple slices was determined by immersing the samples in distilled water at room temperature. A given amount of the dried products was weighed accurately to 0.01 g and placed in a 500 mL baker with distilled water on a 1:100 (w/v) basis, and allowed to rehydrate for 50 min. Then, after removing from the baker and draining the water over a mesh for 2 min, the rehydrated samples were weighed and the rehydration ratio was computed as follows:

$$\text{Rehydration ratio} = \frac{W_r - W_d}{W_d} \quad (12)$$

where, W_r and W_d are the masses (g) of rehydrated and dry apple slices respectively.

2.9. Statistical analysis

The data obtained from the experiments for each treatment (with two replications) was statistically analyzed using SAS (9.2) computer program and practicing a 3 × 3 × 2 split factorial design. The effects of the drying air temperature, drying air velocity, and speed of the tray rotation on the studied parameters ($p < 0.01$) were evaluated and compared by the Duncan multiple range test.

3. Results and discussion

3.1. Drying time

The influences of the drying air temperature and velocity as well as the tray rotation speed on the dehydration time of the apple slices are presented in Figure 1. The average values for the process ranged from 124 min (80 °C, 2 m s^{-1} and 12 rpm) to 344 min (50 °C and 1 m s^{-1} without tray rotation). As shown in the figure and based on the analysis of the variance, increasing the air temperature in the practiced range caused significant ($P < 0.05$) decrement in the process duration. For example, at the constant speed of 6 rpm and flow rate of 1 m s^{-1}, the drying time was reduced for aboutb 29 % and 25 % by changing the air temperature from 50 to 65 °C, and from 65 to 80 °C respectively. In general, higher temperatures result in the facilitated transfer of heat between the air stream and drying samples and consequently, enhance the moisture removal rate. Furthermore, increasing temperature increases the interfacial moisture concentration of the material and leads to the faster moisture removal. In case of the hot air drying, some researchers have reported findings for different biological products. Torki-Harchegani et al. (2016) observed that the times required for drying peppermint leaves at the temperatures of 50, 60 and 70 °C were about 270, 175 and 110 min respectively [6]. Beigi (2017) dried wormwood leaves atthe constant air velocity of 0.7 m s^{-1} and temperatures of 50, 60 and 70 °C, and reported the process times to be 140, 80 and 40 min respectively [18].

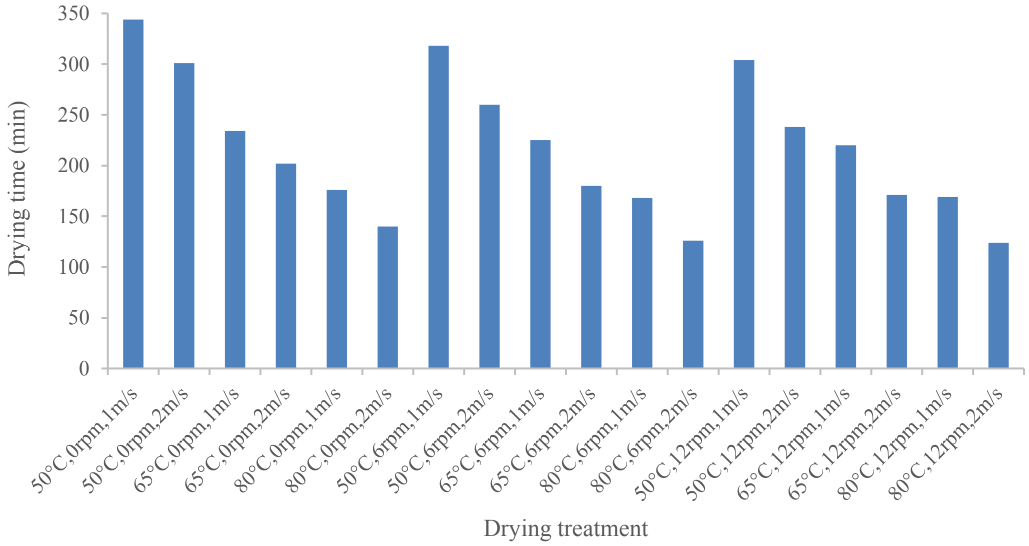

Figure 1. Average drying time for the dehydration of the apple slices in the rotating-tray convective dryer.

The obtained results revealed that the drying air velocity significantly ($P < 0.05$) reduced the drying time where, at all applied temperatures and rotation speeds, the duration was lower at higher air velocities. For example, in the case of the tray rotation speed of 12 rpm, increasing the flow arte from 1 to 2 m s^{-1} resulted in the approximate reduction of 22 %, 23 % and 27 % in the duration for the air temperatures of 50, 65 and 80 °C respectively. The observation originates the fact that, in addition to the material resistance itself, the boundary layer is the other main resistance source acting as an insulating air layer and limits the dehydration. At higher air flow rates, the boundary layer resistance is reduced and subsequently, the drying rate is increased. The observation is in well agreement with the findings reported for the convective drying of different products such as onion in a fluidized bed dryer equipped with a heat pump dehumidifier [21], hawthorn fruit using a convective dryer at the air temperatures of 50, 60 and 70 °C and air velocities of 0.5, 0.9 and 1.3 m s^{-1} [22], and aloe vera puree using hot air in combination with far-infrared radiation and high-voltage electric field [23].

The influence of the rotation speed on the drying duration of the apple slices can be discussed according to the results represented in Table 2. As shown, increasing the tray rotation speed reduced the process duration. The observation is mainly due to the reduced temperature gradients inside the drying chamber by the tray rotation. The phenomenon results in the homogenous and accelerated moisture removal from the drying materials [16]. As presented (Table 2), changing the tray rotation speeds from 0 to 6 rpm, and from 0 to 12 rpm led to average reductions of 8.51 % and 11.5 % in the dehydration times respectively where the variance analysis revealed that, the speed significantly ($P < 0.05$) influenced the time. But, the effect of increasing the rotation speed from 6 to 12 rpm on the drying time was an average of 3.4 % reduction in the drying time which was not statistically significant. As it can be seen from the results, for all experienced temperatures, the effect of the tray rotation on the process time was more observed at higher air velocities. The observation may be justified due to the existence of the higher air mass and more temperature gradients inside the chamber at the higher inlet air velocity, where the tray rotation could be more effective in agitating the air and reducing the temperature gradients. Based on the obtained results represented in Table 2, the contribution of the tray rotation to the drying time is decreased by increasing temperature. At the lower temperatures, the mass evaporation potential of the drying air is lower and therefore, the contribution of the rotation to the mass transfer driving force is more significant. Santos-Sánchez et al. (2012) used a rotating tray dryer to dehydrate tomato slices applying the temperatures of 45, 50 and 60 °C and flow rates of 0.6 and 1.2 m s^{-1} without and with the (20 rpm) tray rotation, and found an average contribution of 6.4 % for the tray rotation in the reduction of the drying time. Furthermore, they reported that the air temperature and velocity had the average of 88.47 % and 4.6 % contributions to the process time respectively [16].

3.2. Evaluation of the mathematical and ANN modeling

The outcomes of the statistical analysis obtained from fitting experimental drying curves to the semi-theoretical models are summarized in Table 3. As shown, of all of them, the Midilli model with the average value of R^2 (0.9961) and RMSE value (0.0134) had the best performance for expressing the drying kinetics.

Table 2
Influence of variation in the tray rotation speed on the reduction (%) of the drying time of the apple slices.

Air temperature (°C)	**Air flow rate (m s^{-1})**	**Reduction in the process duration (%)**			
		Variation in tray rotation speed			
		0→6 rpm	**6→12 rpm**	**0→12 rpm**	**Average**
50	1	7.37	4.47	11.51	7.78
	2	13.41	8.44	20.71	14.19
65	1	5.02	0.84	5.82	3.89
	2	10.57	5.25	15.27	10.36
80	1	4.47	0	4.11	2.86
	2	10.22	1.49	11.56	7.76
Average		8.51	3.4	11.50	

As mentioned before, in the present work, various stes of different hidden layers and neurons with some transfer functions were used and the capability of artificial neural networks (ANNs) for predicting the MR curves was estimated and compared. A summary of the best neural network topologies, and transfer functions in predicting MR for the apple slices is presented in Table 4. As shown, all networks have good prediction accuracy. Among the ANNs shown in the table, the ANN with Log-Lin transfer function and topology of 4–15–1 was the most accurate network for predicting the moisture ratio with the $R^2=0.9984$ and the RMSE=0.0106.

To evaluate the performance of the mathematical modeling and artificial neural network technique, the obtained statistical indices (R^2 and RMSE) for them were compared. The comparison results indicated that, in general, ANN had the better capability to model the drying curves. Some researchers reported the higher accuracy of ANNs in predicting drying curves compared to the mathematical thin-layer models for different products such as white mulberry [19] and onion [21].

Table 3
Statistical comparison among the practiced mathematical models for fitting of the drying curves.

Model	**Model expression**	**R^2**	**RMSE**
Newton	$\mathrm{MR} = \exp(-\mathrm{kt})$	0.9769	0.0358
Aghbashlo et al.	$\mathrm{MR} = \exp(\mathrm{k_1t}/(1 + \mathrm{k_2t}))$	0.9932	0.0171
Page	$\mathrm{MR} = \exp(-\mathrm{kt^n})$	0.9951	0.0150
Logarithmic	$\mathrm{MR} = \mathrm{a}\exp(-\mathrm{kt}) + \mathrm{b}$	0.9948	0.0154
Wang and Singh	$1 + \mathrm{at} + \mathrm{bt^2}$	0.9936	0.0176
Midilli	$\mathrm{MR} = \mathrm{a}\exp(-\mathrm{kt^n}) + \mathrm{bt}$	0.9961	0.0134

Table 4

The best selected ANNs for predicting the drying kinetics.

Training algorithm	Transfer function	Number of layers and neurons	Epoch	R^2	RMSE
LM	Tan-Tan	4-10-1	165	0.9975	0.0134
LM	Tan-Lin	4-12-1	239	0.9980	0.0121
LM	log-Lin	4-12-1	77	0.9979	0.0123
LM	Log-Lin	4-15-1	224	0.9984	0.0106

3.3. Diffusivity

The determined moisture diffusivities are listed in Table 5. As shown, the averages changed from 2.708×10^{-9} m^2 s^{-1} to 6.116×10^{-9} m^2 s^{-1}, which are generally in the range given for food products (10^{-11} to 10^{-6} m^2 s^{-1}) [24]. Furthermore, the determined moisture diffusivity could be compared with the results reported for drying apple presented in Table 6. The differences among the reported moisture diffusivities probably arise from the product diversity as well as drying equipment and conditions.

Table 5

Average effective moisture diffusivity (D) and the coefficient of determination (R^2) obtained for the apple slices.

Air temperature (°C)	Rotation speed of tray (rpm)	Air flow rate (m s^{-1}) 1: D ($\times10^{-9}$ m^2 s^{-1})	1: R^2	2: D ($\times10^{-9}$ m^2 s^{-1})	2: R^2
50	0	2.708	0980	3.073	0.981
	6	3.377	0.980	4.138	0.971
	12	3.408	0.975	4.290	0.975
65	0	3.834	0.962	4.838	0.977
	6	4.899	0.975	5.994	0.968
	12	4.960	0.971	6.116	0.972
80	0	5.173	0.949	6.511	0.971
	6	6.572	0.961	8.215	0.973
	12	6.897	0.973	8.337	0.971

Table 6

The effective moisture diffusivities found for the convective drying of apple slices under different conditions.

Drying conditions	D (m^2 s^{-1})	References
Air temperature: 40-60 °C Air velocity: 0.8 m s^{-1} Sample thickness: 5 and 9 mm	2.27×10^{-10}-4.97×10^{-10}	[25]

Air temperature: 40 °C Air velocity: 2.5 m s^{-1} Sample thickness: 4 mm	2.36×10^{-8}	[26]
Air temperature: 40-80 °C Air flow arte: 0.5-1.5 m s^{-1} Sample thickness: 5 mm	3.22×10^{-9}-15.30×10^{-9}	[27]
Air temperature: 50-70 °C Air velocity: 1-2 m s^{-1} Sample thickness: 5 mm	6.75×10^{-10}-1.28×10^{-9}	[17]
Air temperature: 35-55 °C Air velocity: 0.2-0.6 m s^{-1} Air humidity: 40-70% Sample thickness: 4 mm	0.48×10^{-10}-2.02×10^{-10}	[28]

As the statistical analysis shows, the diffusivity values increase significantly ($P < 0.05$) by increasing the temperature, which is in well agreement with the findings reported for drying different fruits and vegetables such as lemon [3] and mushroom [29]. In general, increasing the temperature results in the lower water viscosity and more activity of the water molecules. The phenomenon leads to the facilitated diffusion of the molecules and subsequently, enhances the effective moisture diffusivity [3]. From the results obtained from the variance analysis, it was revealed that the airflow rate has significantly ($P < 0.05$) improved the moisture diffusion inside the samples.

Furthermore, tray rotation increased the diffusivity, which is consistent with the finding of Santos-Sánchez et al. (2012) [16] reported for tomato slices in a rotating tray dryer. It is worth noting that, in general, changing the tray rotation rate from 0 to 6 rpm caused significant ($P < 0.05$) increment in the diffusivity of the samples while increasing the speed from 6 to 12 rpm did not significantly influence the diffusivity. The greatest contribution of the tray rotation to the moisture diffusivity was found to be the increment of 39.60 %, and observed for changing the speed from 0 to 12 rpm at 50 °C and 2 m s^{-1}. While, the minimum contribution (0.92 %) to the increment of the moisture diffusivity was obtained for the tray speed increasing from 6 to 12 rpm at 50 °C and 1 m s^{-1}.

3.4. Activation energy

The needed energy to initiate the moisture diffusion is measured by the activation energy. The calculated average values for the activation energy are listed in Table 7. As shown, the activation energy amounts vary between 20.47 kJ mol^{-1} and 23.80 kJ mol^{-1} which are comparable with those reported for mulberry dried in a combined hot air-infrared power dryer (31.15-56.09 kJ mol^{-1}) [11], mutra berries dried in an infrared-convective dryer (79.40-90.23 kJ mol^{-1}) [30], and passion fruit peels dried in a convective dryer (29.57-34.73 kJ mol^{-1}) [31].

Table 7
Average activation energy (E_a) and coefficient of the determination (R^2) obtained for the apple slices.

Air flow rate (m s^{-1})	Rotation speed of tray (rpm)	E_a (kJ mol^{-1})	R^2
1	0	20.47	0.9997
	6	21.08	0.9982
	12	22.30	0.9929
2	0	23.80	0.9911
	6	21.69	0.9996
	12	21.02	0.9998

3.5. Color

From the digital images taken of the fresh and dried apple slices, the color indices including L*, a* and b* were determined. It is worth to note that the indices for each experiment were normalized since the initial values for the fresh samples were different. The obtained results for the color parameters are represented in Table 8. As the results show, for all drying treatments, the normalized lightness of the dried apple slices is slightly more than unit indicating that the lightness of the apple slices has increased after drying. The observation is possibly due to the degradation of chlorophyll and carotenoids in the dried samples. In general, statistical analysis indicated that the drying parameters had no significant ($p > 0.05$) effect on the lightness values of the samples. The same observation was reported by Aghilinategh et al. (2016) [32] for the intermittent microwave/convective drying of apple slices. Baini and Langrish (2009) [33] stated that the observation could be attributed to a reduction in the construction of the brown pigment and a cessation in the non-enzymatic browning because of low moisture contents of the samples during the falling rate period of drying.

Table 8
Average values for the color parameters of the apple slices dried under the different practiced drying conditions.

Air temperature (°C)	Air velocity (m s^{-1})	Tray rotating speed (rpm)	ΔE	L^*/L^*_0	a^*/a^*_0	b^*/b^*_0
50	1	0	10.62±0.32	1.08±0.02	0.67±0.03	1.24±0.03
		6	10.73±0.31	1.11±0.02	0.75±0.07	1.21±0.08
		12	9.40±0.43	1.08±0.01	0.76±0.04	1.21±0.02
	2	0	10.44±2.23	1.10±0.03	0.71±0.13	1.21±0.06
		6	9.65±0.94	1.08±0.01	0.76±0.03	1.21±0.05
		12	10.73±1.07	1.08±0.02	0.76±0.05	1.24±0.02
65	1	0	10.94±0.72	1.08±0.03	0.87±0.05	1.27±0.06
		6	11.00±0.92	1.10±0.02	0.83±0.01	1.25±0.01
		12	11.24±1.27	1.08±0.03	0.76±0.04	1.28±0.03

	2	0	11.34±0.35	1.07±0.01	0.63±0.04	1.26±0.08
		6	11.16±1.20	1.10±0.02	0.82±0.02	1.24±0.02
		12	10.97±0.27	1.07±0.01	0.80±0.09	1.27±0.01
80	1	0	11.57±0.49	1.11±0.02	0.85±0.10	1.25±0.03
		6	11.97±0.98	1.11±0.02	0.87±0.02	1.27±0.02
		12	11.69±2.43	1.09±0.00	0.79±0.06	1.28±0.10
	2	0	12.07±0.86	1.11±0.02	0.77±0.09	1.25±0.08
		6	11.39±1.13	11.09±0.01	0.85±0.04	1.28±0.04
		12	11.01±0.47	1.08±0.02	0.84±0.10	1.28±0.05

Both of the initial and final redness values respectively obtained for the fresh and dried apple slices were negative representing the greenness of the samples. The redness values for the dried samples were greater than the values determined for the fresh samples revealing that drying process resulted in more red slices. This variation in the index could be related to the reactions of the non-enzymatic Maillard browning and the formation of brown pigments during the moisture removal process. In addition, during the thermal processing, carotenoids and anthocyanin concentrations are responsible for the variation of the red color of food products [34]. Fernandez et al. (2005) [35] reported that the anthocyanin of apple slices was increased during the convective hot air drying. In addition, Quan et al. (2014) [36] found that the redness rose after the intermittent microwave convective drying of apple slices and microwave drying of chips potato. It is worth noting that, because of negative magnitudes, the values for the normalized redness of the samples represented in Table 8 are inversely proportional to the actual redness. From the obtained results, the normalized redness of the apple slices increased meaningfully ($p < 0.05$) by increasing the drying air temperature. In fact, the Maillard reaction is promoted at higher temperatures. The same finding for the influence of the drying air temperature on the normalized redness of the dried slices has been reported by Vega-Galvez et al. (2012) [27]. The effect of the air velocity on the redness was not significant ($p > 0.05$) which is in agreement with the observation reported by Seiiedlou et al. (2010) [37] in term of the effect of the air velocity on the parameter.

The yellowness of the samples increased significantly ($p < 0.05$) after dehydration where the b^*/b^*_0 was obtained to be more than unit under all drying conditions (Table 8). The observation could be attributed to the brown pigments development by non-enzymatic Maillard reactions in the samples during the dehydration process. More yellowness of the convectively dried apple slices in comparison with the fresh samples have been found by Nadian et al. (2015) [38] and Aghilinategh et al. (2016) [32]. The observation could be risen from the volume shrinkage of the dried samples resulting in an enhanced concentration of carotenoids in the apple slices and consequently changing the color to near to the yellowish region. According to the results, increasing the drying air temperature augmented fairly the normalized yellowness. The finding could be related to the fact that the higher drying temperature resulted in the faster non-enzymatic browning reaction and thus enhanced the yellowness. Furthermore, it is worth to note that the drying velocity and tray rotation speed had no effect on yellowness ($p > 0.05$).

From the results obtained and represented in Table 8 and the variance analysis, the drying air temperature had significant ($p < 0.01$) effect on the total color difference (ΔE) in the dried slices where the difference increased considerably with the temperature. The same finding was reported by Sacilik and Elicin (2006) [25] for the effect of the temperature on the total color difference in the dried organic apple slices after the convective drying. However, the influence of both the drying air velocity and tray speed on the total color difference was not significant ($p > 0.05$). It can be concluded that the color of the dried product was dramatically degraded by increasing the drying temperature.

3.6. Shrinkage and rehydration ratio

The average values obtained for the shrinkage and rehydration ratios of the apple slices dried under different drying conditions are shown in Table 9. From the results and statistical analysis, the shrinkage of the dried apple was significantly ($p < 0.01$) decreased by increasing the drying air temperature. It could be related to the faster moisture removal from the slices at higher drying air temperatures where the case hardening occurs at the first stages of the dehydration process and prevents the further shrinkage of the drying sample. In fact, at a high drying temperature, the external moisture content of the samples reduced so rapidly that the surface became stiff or rigid, limiting the ensuing shrinkage. In the other word, the surface hardening does not give adequate time to the product viscoelastic matrix to shrink back completely into the voids previously filled with water. Similar result has been reported by Lewicki and Jakubczyk (2004) [39] for the hot air drying of apple slices. Also, since the drying air temperature is the main factor in hardening the sample surface, the influence of the other studied variables (including the air velocity and tray rotation speed) on the shrinkage was not significant ($p > 0.05$).

Table 9

Average values for the shrinkage and rehydration ratio of the apple slices dried under the different drying conditions.

Air temperature (°C)	**Tray rotation speed (rpm)**	**Air velocity (m s^{-1})**			
		1		2	
		Shrinkage (%)	Rehydration ratio	Shrinkage (%)	Rehydration ratio
50	0	73.21±0.41	1.76±0.13	74.70±0.69	1.86±0.13
	6	74.20±0.52	1.71±0.04	73.41±1.47	1.70±0.08
	12	74.26±1.98	1.70±0.13	74.88±1.03	1.77±0.31
65	0	72.60±1.98	1.75±0.06	73.30±0.96	1.91±0.20
	6	73.13±1.81	1.82±0.07	72.30±0.94	1.81±0.06
	12	73.26±1.40	1.82±0.09	73.80±0.52	1.86±0.02
80	0	71.88±0.75	1.82±0.02	71.98±1.38	2.01±0.11
	6	71.22±2.36	1.95±0.07	72.70±0.22	1.96±0.02
	12	71.91±1.20	1.99±0.29	71.95±0.71	1.94±0.28

In general, the rehydration process of the dried biological products with cellular structures such as vegetables and fruits is a very complex phenomenon, which is affected by the inherent characteristics of the products as well as drying and rehydration conditions. The obtained results in this study (Table 9) showed that the rehydration ratio increased by increasing the tray rotation speed as well as drying air temperature and velocity. However, the variance analysis revealed that the ratio was affected significantly by the temperature ($p < 0.05$) while the influence of the air velocity and tray speed was not meaningful ($p > 0.05$). Higher drying temperatures may cause dried slices with more porous structure resulting in the facilitated water penetration and higher rehydration ratio. A similar finding in term of the influence of the drying temperature on the rehydration capacity of dried biological products was reported for apple by Vega-Galvez et al. (2012) [27] and Sacilik and Elicin (2006) [25].

4. Conclusions

The drying experiments of apple slices were carried out using a rotating-tray convective drying system with different levels of the tray rotation speed as well as drying air temperatures and flow rates. The influences of the operating parameters on the moisture removal properties of the slices were investigated. The conclusions of the research can be summarized as follows:

- Generally, all of the variables of the operation meaningfully ($P < 0.05$) affected the process duration and the samples diffusivity. A reduction in the dehydration time and an increment in the moisture diffusivity were induced by increasing the drying air temperature and velocity as well as tray rotation speed.
- In comparison with the thin layer models, artificial neural networks had better accuracy for modeling the drying curves.
- The average activation energies were calculated to be in the range of 20.47-23.80 kJ mol^{-1}, and were generally in the range found for biological products.
- Higher drying air temperatures and velocities generally destroyed the quality of the final products
- From the findings, it could be concluded that, uniform distribution of the air stream over the drying trays in convective dryers could augment the system performance.

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