AN EXPERIMENTAL STUDY ON THIN-LAYER DRYING DRYING CHARACTERISTICS OF APPLE SLICES

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Abstract–– **In this experimental study, cultivar of Granny Smith apple slices were dried by using convective hot air tray dryer. Before drying process, the pretreatment methods with ascorbic acid and citric acid solution (0.5% + 0.5%), blanching (80°C and 1 min) and potassium carbonate solution (4%) were carried out. Control samples were dried naturally without any pretreatments. Temperatures for hot air convective drying were decided as 50, 60, 70 and 80°C with constant air velocity of 2 m/s in the cabinet dryer. Throughout the drying process, constant drying period was not observed. Once the temperatures increased from 50 to 80°C, drying rate also increased. Well-known mathematical models such as Henderson & Pabis, Page, Midilli & Kucuk, Wang & Singh and Agbashlo *et al.* were compared with each other to specify the change of moisture inside the material. Consequently, Midilli & Kucuk model was chosen the best model to explain the drying characteristics of the samples with all drying conditions. Diffusivity coefficients of the moisture transfer inside the apple slices at different temperatures were calculated with the help of Fick's second law of diffusion. The values of diffusion coefficients over the mentioned temperature range changed between 4.804×10^{-10} m^2/s and 1.739×10^{-9} m^2/s. The activation energy values of the drying process were calculated by Arrhenius type equation and found to be 36.1, 32.5, 29.8 and 32.1 kJ/mol for potassium carbonate, citric acid and ascorbic acid mixture, blanching and control samples, respectively.**

Keywords– **Convective drying, apple drying, mathematical modeling, pretreatment, activation energy**

I. INTRODUCTION

Apple (*Malus domestica*) is a type of fruit belonging to rose family (Rosaceae). It is widely grown all over the world. The world's apple production reached 87236221 metric tons in 2019. China, United States of America, Turkey, Poland and India are the leading apple-growing countries. The amount of apple production in Turkey was 3618752 metric tons in 2019 (FAO, 2020). Apple fruit is consumed either fresh or processed like snack, jam, juice and dried apple. Nutritional content of apple includes minerals, carbohydrates and fibers. To exploit these content rich in nutritional value, moisture level inside the fruit need to be decreased to a certain level (Kara and Doymaz, 2015).

Foods, especially fruits and vegetables, have limited lifespan due to highly moisture content contained in their structure. To increase the shelf-life of these materials, conventional drying methods are widely used through the world. Drying techniques are special to materials and not only used for conservation aim but also used for producing a variety of healthy and functional snacks. Drying processes ability to make space savings by reducing the volume of the material. During drying process, temperature effect on biomaterials can cause undesired reactions such as browning reaction and nutrition degradation. Quality characteristics of fruits and vegetables are evaluated with respect to the color index, odor level, texture firmness. Consumers pay attention to these finished products' quality aspects to choose the products (Kirmaci *et al.*, 2013).

A great deal of different dryers and drying techniques exist to turn the foods into value added products. Some of drying techniques accessible to almost all people are conventional hot air drying and sun drying. Sun drying holds conventional problems such as weather dependence environment, labor intensive condition and contamination risks unless the drying space with heating air is isolated from outside (Sagar and Kumar, 2010). Conventional hot air drying also has some drawbacks in basic unit operation processes. This type of drying method needs high temperature treatment with long processing time. In this case, the energy consumption unavoidably increases and biomaterials beneficial to human health also degrade (Baysal *et al.*, 2015). Taken into the consideration, all these problems about hot air drying and sun drying, hot air dryers are more advantageous to sun dryers. Experts in dried food production are accustomed to hot air dryers. These dryers are easy to operate and can be combined with other type of dryers to increase the efficiency of the process (Guiné *et al.*, 2014).

Efficiency of hot air-drying system is generally low and evaporation of water from foods demand high energy because of latent heat of water evaporation. Only drying unit operation uses up 15% of all energy in France, United States of America and Canada while the energy uptake for drying changes between 20% and 25% in Denmark and Germany (Beigi, 2016a).

Fresh apple slices before drying is highly poor resistance to physical and chemical changes because of their soft texture and polyphenol oxidases enzyme content. Polyphenols contained in apples can provoke enzymatic browning and undesired reactions. Inhibition of

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these types of reactions is carried out with the aid of pretreatment methods. Pretreatment methods in drying processes are separated in two categories as chemical and physical pretreatments. Chemical pretreatment is generally applied to the material dried with the addition of chemical solution of citric acid and ascorbic acid solution. The most frequently applied physical pretreatment method by researchers is blanching. To prepare durable and stable dried products, pretreatments and hot air drying are combined (Heras-Ramirez *et al.*, 2012). Pretreatment methods with ascorbic acid and citric acid solution results in better color and rehydration characteristics compared to apple slices without pretreatment (Doymaz, 2009).

The main objectives of this study were to investigate the effect of drying temperatures and pretreatments affected on drying time, fit the experimental data to five thin-layer drying models, and to calculate the effective moisture diffusivity and activation energy.

II. METHODS

A. Apple samples

The cultivar of Granny Smith was purchased from local market from İstanbul, Turkey. They were kept at 4°C before drying process. To choose the apple for drying, special care was paid not to get bruised, rotten and damaged ones. To prepare the samples to the drying process, the apples were allowed to stand at room temperature for 30 min. before the drying process to distribute the moisture content uniformly throughout.

B. Pretreatment applications

Chemical pretreatments were applied with the solution of citric acid (0.5%) and ascorbic acid (0.5%) mixture solution and potassium carbonate (4%) solution. The exposure time of each chemical pretreatment of the apple slices is 1 minute. Physical pretreatment method was blanching. Pretreatment temperature and period for blanching was chosen as 80°C and 1 minute, respectively.

C. Experimental device

The drying experiments were carried out in a laboratory scale cabinet dryer that is the model of APV & PASILAC, UK. Dryer used in the experiments is composed of a centrifugal fan to source the air-flow, an air filter, an electronic temperature controller and an electric heater. The air temperature in the dryer is regulated to ±1 °C using a temperature controller. A centrifugal fan and fan speed control unit was used for regulating the air velocity. The model type of TESTO 440 Vane Probe Anemometer (AM-4201, Lutron, Taipei, Taiwan) was the apparatus to measure the velocity of the air. The air was forced to flow parallel to the bed on which samples were spread. The air taken from the heating unit and increased to the desired temperature was sent to the drying chamber. The flow cross-section of the heating chamber is in the form of square with the dimensions of 30 × 30 cm. During the experiments, a digital balance (BB3000, Mettler-Toledo AG, Grefensee, Switzerland) with a sensitivity of 0.1 g. was used to measure weight loss of the apple samples.

D. Drying procedure

Initial moisture content analysis

The initial moisture content of the apple slices was measured with an incubator (Selecta, Barcelona, Spain). The incubator was operated at 105±2°C for 5 h to dry the samples to 15% moisture content in dry basis. Five different samples in petri dishes were dried and the average value of the initial moisture content was found as 85.45% (wet basis). After drying section inside the incubator, the samples were taken to the desiccator for about 10 min to cool the samples to room temperature and prevent the samples from humidifying because of the difference in moisture content with the environment.

Drying of apple slices

Drying experiments were performed in the cabinet dryer with hot air heating mechanism. Temperatures for the process were selected between 50 and 80°C with 10°C of increment in each experiment. Drying air velocity was fitted to the value of 2±0.1 m/s. The cabinet dryer was kept working for 30 min to attain steady-state condition before the samples loaded into the dryer. Apple samples were sliced with laboratory scale slicer in 7 mm thickness. Then, the apple slices (100±1 g) were uniformly distributed onto the trays in a thin-layer inside the cabinet dryer. As the experiments continued, samples were taken out from the cabinet dryer and weighed with analytical balance in 15 min. interval to determine the moisture loss of the apple slices. The drying process was preceded till the moisture level in the samples reduced to a level of 0.13 kg water/kg dry matter in dry basis. After the drying process ended, dried samples were cooled down to room temperature and packaged with low density polyethylene (LDPE) bags. These bags were sealed with special equipment (Krups Vacupack Plus F380, Germany) that uses heat treatment for sealing. Drying trials performed in the study were done three times to increase credibility.

Mathematical modeling

Moisture content theoretically was calculated with the equation below (Kirmaci *et al.*, 2013):

$$M = \frac{M_w}{M_d} \tag{1}$$

where M is the moisture content (kg water/kg dry matter), M_w is the water content in kg and M_d is the dry matter content in the material dried.

In addition, dimensionless moisture ratio is expressed in equation form as below (Kumar *et al.*, 2012):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{2}$$

where MR is the dimensionless moisture ratio, M_t is the moisture content at any time in kg water/kg dry matter, M_0 is the initial moisture content in kg water/kg dry matter, and M_e is the equilibrium moisture content at the end of the drying process in kg water/kg dry matter.

The equilibrium moisture content (M_e) is relatively small compared with M_0, especially for long drying time, which was assumed to be zero. So MR can be simplified to (Faal *et al.*, 2015):

$$MR = \frac{M_t}{M_0} \quad (3)$$

E. Effective diffusion coefficient and activation energy

During the drying of fruits and vegetables, thin layer method finds application area, and Fick's second law is used for unsteady state drying system to calculate the dimensionless moisture ratio. The equation is given below:

$$\frac{\partial M}{\partial t} = \nabla.\left(D_{eff}.\nabla M\right) \quad (4)$$

The solution of the equation above was recommended by Crank (1975). He accepted the geometry of the material dried with infinite length and reasonable thickness. The moisture content inside the material was assumed to be distributed homogenously and shrinkage due to the reduction of water amount during drying was neglected. External resistance to diffusion and constant diffusivity through the material were also assumed. The solution of Eq. (4) with all these assumptions (Crank, 1975):

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\,\pi^2 D_{eff} t}{4L^2}\right) \quad (5)$$

In the Eq. (5), D_{eff} is the effective diffusion coefficient in m^2/s, L is the half thickness of the material dried in m, and t is the time for drying in s. In case of long drying time, the first term from the solution of the Eq. (5) is used to calculate dimensionless moisture ratio. Other terms in the solution are neglected (Kara and Doymaz, 2015):

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (6)$$

The curve of $\ln(MR)$ is drawn with respect to drying time and the slope of the curve is used to calculate the effective diffusion coefficient.

$$K = \frac{\pi^2 D_{eff}}{4L^2} \quad (7)$$

The relationship between effective diffusion coefficient and temperature is expressed with Arrhenius type of equation (Kara and Doymaz, 2015):

$$D_{eff} = D_0\exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad (8)$$

In the Eq. (8), D_0 is the pre-exponential factor in m^2/s, D_{eff} is the effective diffusion coefficient in m^2/s, E_a is the activation energy in kJ/mol, R is the universal gas constant in kJ/mol.K, and T is the drying temperature in (°C). The value of the activation energy is calculated from the slope of the curve drawn between $\ln(D_{eff})$ and $1/(T + 273.15)$.

F. Modeling of the thin-layer drying

In drying process, modeling is indispensable for drying kinetics and controlling the parameters needed for efficient drying. Additionally, it is also popular applied method to choose which dryer type is used. By using the mathematical modeling, the simultaneous heat and mass transfer carried out in drying process is easily analyzed to produce value added products from raw materials and optimize the process conditions (Meisami-asl *et al.*, 2009). During the modeling of the drying phenomenon, data obtained from experimental study is fitted to the semi-theoretical models to gain insight about the change in moisture content of the material. In this experimental study, Henderson & Pabis, Page, Midilli & Kucuk, Wang & Singh and Agbashlo *et al.* models were used to evaluate the change in moisture content. These are given in Table 1.

Table 1. Semi-theoretical model equations for evaluating moisture content

Model Name	Equation	References
Henderson & Pabis	$MR = a\exp(-kt)$	Ndukwu *et. al.* (2017)
Page	$MR = \exp(-kt^n)$	Saxena and Dash (2014)
Midilli & Kucuk	$MR = a\exp(-kt^n) + bt$	Midilli and Kucuk (2003)
Wang & Singh	$MR = 1 + at + bt^2$	Beigi (2016b)
Agbashlo *et al.*	$MR = \exp\left(-\frac{at}{1+bt}\right)$	Onwude *et al.* (2016)

G. Statistical Analysis

Regression analysis of the experimental study is performed to verify data fit. Statistica (Statsoft, Inc., Tulsa, OK) was the software package used to analyze regression coefficient. To choose the best mathematical model defining the drying curve, regression coefficient (R^2) was used as a criterion. Furthermore, chi-square (χ^2) and root mean square error (RMSE) were also used as statistical measurements to assess the drying performance.

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N-z} \quad (9)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \quad (10)$$

MR_{exp} and MR_{pre} shown above in the Eq. (9) and Eq. (10) are experimental dimensionless moisture ratio and moisture ratio calculated with mathematical model equations, respectively. N is the number of observations and z is the number of constants in the mathematical equations.

III. RESULTS AND DISCUSSION

A. Drying curves

Figure 1-4 shows the drying curves of experimental study of apple slice at temperature scales with 10°C increment between 50 and 80°C. The moisture level inside apple slices were reduced from 5.86 kg water/kg dry matter in wet basis to 0.13 kg water/kg dry matter in dry basis. With the temperature effect, pretreatment method applied to apple slices decreased the drying time. The samples pretreated with potassium carbonate showed shorter drying time compared to pretreatment with blanching and citric acid and ascorbic acid mixture, and control samples at all temperature levels. At 60°C, while control samples dried in 420 min., the samples treated with potassium carbonate dried in 330 min. In addition, pretreated samples with citric acid and ascorbic acid mixture and blanching method proved to dry much shorter time than control samples as 390 and 375 min., respectively. Other temperature scales (50, 70 and 80°C) for this study showed similar results to the samples dried at 60°C. The results are given in Figs. 1-4.

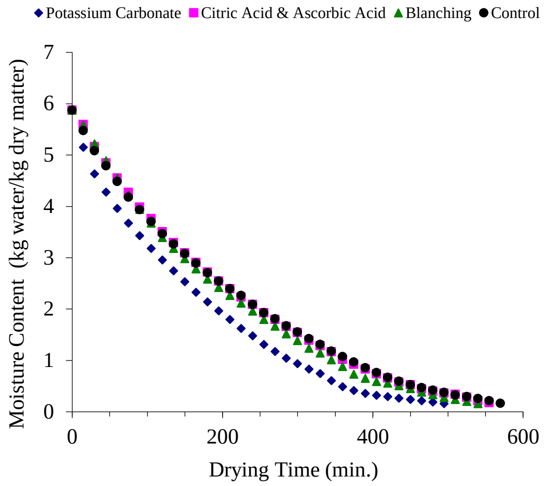

Fig. 1. Change in moisture content versus drying time at 50°C.

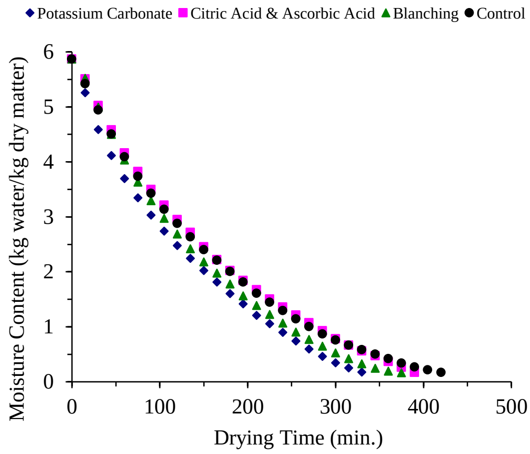

Fig. 2. Change in moisture content versus drying time at 60°C.

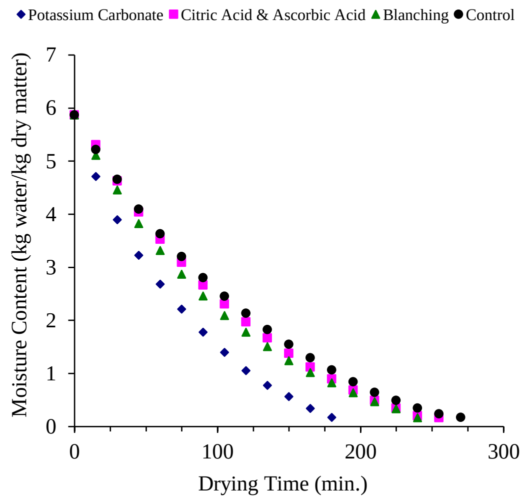

Fig. 3. Change in moisture content versus drying time at 70°C.

From the results of the experimental study, there was a reduction of 22% in shelf-life of the drying time with these samples pretreated with potassium carbonate when compared to control samples. Similar results were seen for the samples pretreated with citric acid and ascorbic acid mixture solution and blanching pretreatment method. About 11% and 8% reduction were observed in self-life of drying time of samples pretreated with blanching method, and citric acid and ascorbic acid mixture solution, respectively. These reduction ratios in drying time were calculated for samples dried at 60°C. Similar results were obtained at other temperatures operated in drying process. From the Fig. 2 and Fig.3, change in drying times for the temperature values of 60°C and 70°C were found between 330 and 420 min., and 180 and 270 min., respectively. For each experiment, 10°C increment in temperature reduced the drying times of apple slices considerably, about 36-46%. Similar results were also reported for apple slices by earlier researchers (Sacilik and Elicin, 2006; Doymaz, 2010).

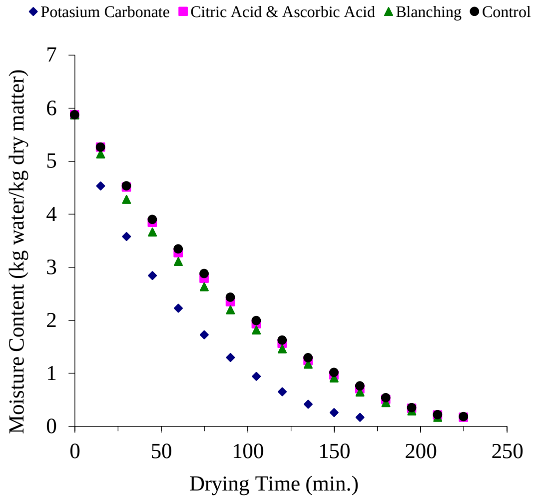

Fig. 4. Change in moisture content versus drying time at 80°C.

Reduction in drying time brings with energy saving. Drying time is affected by drying air temperature. With the temperature increase in drying process, the heat and mass transfer coefficient also increase between the material dried and drying air media, which causes the moisture transfer to accelerate. As a result, the experiment carried out in drying of apple slices proved that drying time decrease with the increase of temperature and application of pretreatment methods such as citric acid and ascorbic acid mixture solution, blanching, and potassium carbonate. It was clear from the experimental study that drying of materials without pretreatment takes much more time compared to samples dipped in chemical solutions and blanched with hot water.

B. Fitting of drying curves

Mathematical modeling was carried out by using the data obtained from the experiments and keeping a curve on the change graph of drying time and moisture content. Nonlinear regression analysis method was used when making the curve. The equations used for mathematical modeling are given in Table 1 and the resulting regression coefficient (R^2), chi-square (χ^2) and root mean square error ($RMSE$) values calculated after modeling are given in Table 2-5. Additionally, model constants (a, b, k, and n) in the model equations calculated with the aid of the Statistica software program are also

Table 2. Models, calculated model constants, the values of R^2, χ^2 and $RMSE$ for the samples pretreated with potassium carbonate solution

Model	Temperature (°C)	Model Constants				R^2	χ^2	$RMSE$
		a	b	k	n			
Henderson & Pabis	50	0.983397	-	0.005954	-	0.9926	0.000574	0.123077
	60	1.009064	-	0.007656	-	0.9929	0.000595	0.090273
	70	1.010544	-	0.014140	-	0.9933	0.000669	0.072100
	80	1.010486	-	0.017252	-	0.9959	0.000430	0.057526
Page	50	-	-	0.005395	1.021766	0.9924	0.000590	0.118565
	60	-	-	0.005745	1.055967	0.9939	0.000513	0.087669
	70	-	-	0.009554	1.086372	0.9952	0.000094	0.024962
	80	-	-	0.012256	1.078034	0.9974	0.000276	0.045773
Midilli & Kucuk	50	0.979785	-0.000188	0.008444	0.905080	**0.9993**	**0.000067**	**0.034300**
	60	1.005516	-0.000449	0.012906	0.847965	**0.9996**	**0.000034**	**0.019634**
	70	0.998688	-0.000714	0.017666	0.898424	**0.9998**	**0.000017**	**0.010078**
	80	0.998047	-0.000434	0.017993	0.958959	**0.9997**	**0.000038**	**0.014891**
Wang & Singh	50	-0.004467	0.000005	-	-	0.9822	0.001386	0.161559
	60	-0.005802	0.000009	-	-	0.9886	0.000957	0.119029
	70	-0.010596	0.000030	-	-	0.9963	0.000737	0.074583
	80	-0.012703	0.000042	-	-	0.9921	0.000842	0.076195
Aghbashlo *et al.*	50	0.005563	-0.000352	-	-	0.9939	0.000469	0.097650
	60	0.006795	-0.000621	-	-	0.9957	0.000355	0.074065
	70	0.012118	-0.001418	-	-	0.9974	0.000258	0.043372
	80	0.015123	-0.001420	-	-	0.9987	0.000132	0.030200

Table 3. Models, calculated model constants, the values of R^2, χ^2 and $RMSE$ for the samples pretreated with citric acid and ascorbic acid mixture solution

Model	Temperature (°C)	Model Constants				R^2	χ^2	$RMSE$
		a	b	k	n			
Henderson & Pabis	50	1.035054	-	0.004766	-	0.9925	0.000621	0.131871
	60	1.037767	-	0.006384	-	0.9995	0.000595	0.095473
	70	1.052291	-	0.010070	-	0.9881	0.001200	0.117760
	80	1.059244	-	0.011715	-	0.9871	0.001381	0.122903
Page	50	-	-	0.002180	1.135426	0.9964	0.000293	0.091680
	60	-	-	0.002994	1.138089	0.9968	0.000275	0.068944
	70	-	-	0.003290	1.223549	0.9967	0.000330	0.062364
	80	-	-	0.003227	1.259357	0.9978	0.000234	0.050712
Midilli & Kucuk	50	1.001241	-0.000166	0.004109	0.993053	**0.9995**	**0.000042**	**0.032956**
	60	1.009719	-0.000270	0.006065	0.970920	**0.9997**	**0.000024**	**0.018029**
	70	1.002418	-0.000377	0.005937	1.066148	**0.9997**	**0.000030**	**0.017101**
	80	1.000745	-0.000301	0.005138	1.140360	**0.9996**	**0.000038**	**0.016768**
Wang & Singh	50	-0.003491	0.000003	-	-	0.9963	0.000307	0.086728
	60	-0.004700	0.000006	-	-	0.9960	0.000338	0.078127
	70	-0.007145	0.000013	-	-	0.9963	0.000104	0.035317
	80	-0.008244	0.000018	-	-	0.9995	0.000046	0.018960
Aghabashlo *et al*.	50	0.003829	-0.000591	-	-	0.9988	0.000096	0.051860
	60	0.005125	-0.000799	-	-	0.9986	0.000117	0.043847
	70	0.007330	-0.001732	-	-	0.9993	0.000067	0.029083
	80	0.008280	-0.002145	-	-	0.9995	0.000041	0.019020

Table 4. Models, calculated model constants, the values of R^2, χ^2 and RMSE for the samples pretreated with blanching method

Model	Temperature (°C)	Model Constants				R^2	χ^2	$RMSE$
		a	b	k	n			
Henderson & Pabis	50	1.045117	-	0.005087	-	0.9926	0.000636	0.129958
	60	1.049446	-	0.007259	-	0.9931	0.000632	0.101256
	70	1.028309	-	0.010535	-	0.9936	0.000601	0.078615
	80	1.039549	-	0.012094	-	0.9905	0.000970	0.094887
Page	50	-	-	0.002063	1.156880	0.9971	0.000242	0.083601
	60	-	-	0.002974	1.165019	0.9976	0.000220	0.061975
	70	-	-	0.005513	1.131517	0.9973	0.000250	0.049562
	80	-	-	0.005045	1.182305	0.9967	0.000329	0.055459
Midilli & Kucuk	50	1.003298	-0.000135	0.003584	1.034316	**0.9993**	**0.000058**	**0.034274**
	60	1.011396	-0.000194	0.005302	1.030600	**0.9995**	**0.000045**	**0.025758**
	70	1.000963	-0.000381	0.009187	0.990465	**0.9999**	**0.000004**	**0.005543**
	80	1.002422	-0.000464	0.008774	1.025899	**0.9997**	**0.000032**	**0.014779**
Wang & Singh	50	-0.003668	0.000004	-	-	0.9970	0.000256	0.078337
	60	-0.005208	0.000007	-	-	0.9966	0.000306	0.074401
	70	-0.007805	0.000016	-	-	0.9962	0.000355	0.062599
	80	-0.008753	0.000020	-	-	0.9979	0.000210	0.041589
Aghbashlo et al.	50	0.003992	-0.000661	-	-	0.9991	0.000077	0.044695
	60	0.005664	-0.000949	-	-	0.9989	0.000100	0.041517
	70	0.008603	-0.001264	-	-	0.9991	0.000082	0.028080
	80	0.009263	-0.001827	-	-	0.9991	0.000091	0.030279

Table 5. Models, calculated model constants, the values of R^2, χ^2 and $RMSE$ for the control samples

Model	Temperature (°C)	Model Constants				R^2	χ^2	$RMSE$
		a	b	k	n			
Henderson & Pabis	50	1.018690	-	0.004690	-	0.9928	0.000576	0.127009
	60	1.028046	-	0.006489	-	0.9948	0.000439	0.091758
	70	1.041821	-	0.009400	-	0.9887	0.001095	0.118959
	80	1.060126	-	0.011431	-	0.9855	0.001557	0.128984
Page	50	-	-	0.002671	1.098508	0.9954	0.000365	0.103532
	60	-	-	0.003554	1.110095	0.9975	0.000019	0.017747
	70	-	-	0.003513	1.195008	0.9960	0.000378	0.070361
	80	-	-	0.003039	1.272273	0.9973	0.000309	0.055685
Midilli & Kucuk	50	0.995632	-0.000191	0.005073	0.949762	**0.9994**	**0.000048**	**0.033490**
	60	1.002234	-0.000179	0.005925	0.988586	**0.9997**	**0.000018**	**0.017378**
	70	0.997075	-0.000397	0.006359	1.033978	**0.9997**	**0.000025**	**0.015171**
	80	0.999145	-0.000350	0.004897	1.140098	**0.9997**	**0.000029**	**0.014488**
Wang & Singh	50	-0.003507	0.000003	-	-	0.9969	0.000487	0.108801
	60	-0.004780	0.000006	-	-	0.9947	0.000446	0.093808
	70	-0.006767	0.000012	-	-	0.9985	0.000140	0.042384
	80	-0.008018	0.000016	-	-	0.9995	0.000047	0.019852
Aghbashlo et al.	50	0.003948	-0.000499	-	-	0.9979	0.000168	0.069121
	60	0.005424	-0.000667	-	-	0.9991	0.000073	0.037042
	70	0.008603	-0.001264	-	-	0.9992	0.000074	0.031898
	80	0.007941	-0.002211	-	-	0.9996	0.000031	0.016757

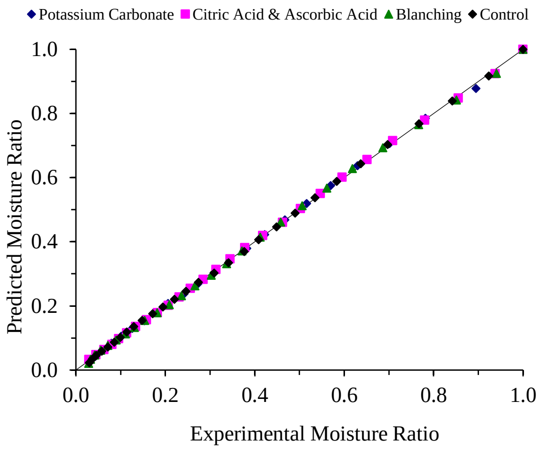

Fig. 5. Comparison of experimental and predicted values of moisture ratio at 60°C.

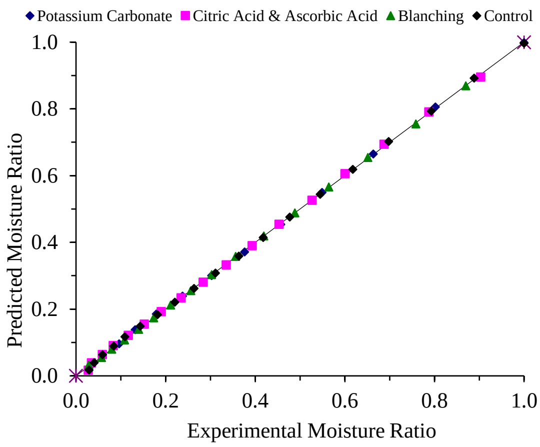

Fig. 6. Comparison of experimental and predicted values of moisture ratio at 70°C.

given at different temperatures (50, 60, 70, and 80°C) with different mathematical models in the Tables 2-5.

When the suitability of the mathematical equations used is controlled, it is desirable that the regression coefficient (R^2) should be as close to the value of 1 as possible and the mean squared error ($RMSE$) value with chi-square (χ^2) are as small as possible. The regression coefficient (R^2) was chosen as the main criterion in the selection of the equation that best describes the drying kinetics of apple slices during the drying process. The mean squared error value ($RMSE$) is an indication of the difference between the empirically obtained results and the calculated values of the mathematical equations. At the same time, the decrease in the value of chi-square χ^2 seems to increase the correspondence between experimental and calculated values.

The regression coefficient (R^2) of the Midilli & Kucuk model was found to be the highest in all temperature conditions and applied pretreatment methods, and the root mean square error ($RMSE$) and chi-square (χ^2) values were found to be smaller than the other models used. With the help of the obtained results, it was understood that the Midilli & Kucuk model best describes the drying process of apple slices. For example, the experimental data obtained at 60°C and 70°C and the moisture content obtained using the Midilli & Kucuk model are shown in Figs. 5 and 6. As seen from the figures, the data obtained with the experimental data is in agreement with the values calculated with the help of the Midilli & Kucuk model.

C. Effective moisture diffusivity and activation energy

The diffusion coefficient of the pretreated and non-pretreated samples during the drying process was calculated separately for each drying temperature by using the Eq. (6). The calculated values for the diffusion coefficient are given in Fig. 7. It was found that the effective diffusion coefficient values of the samples dried in the cabinet dryer varied between 4.804×10^{-10} m^2/s and 1.275×10^{-9} m^2/s for the control group, 6.046×10^{-10} and

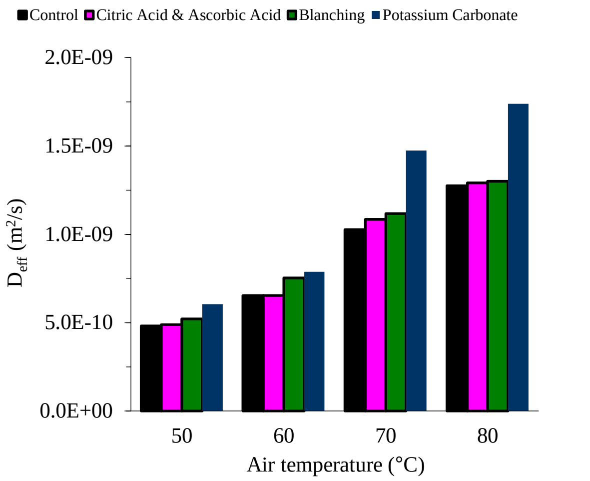

Fig. 7. Change of the effective diffusion coefficient with respect to time in the drying of apple slices.

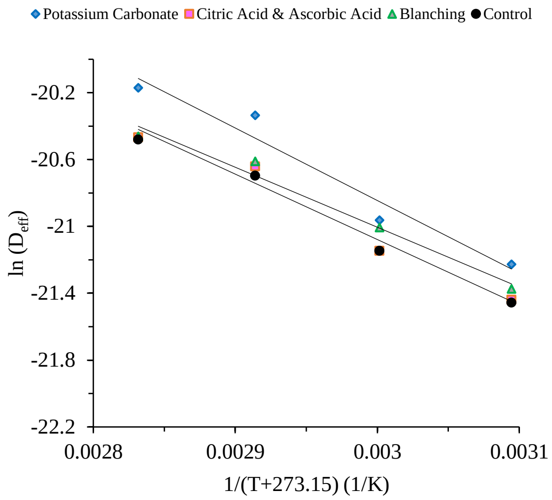

Fig. 8. Temperature effect on the effective diffusion coefficient.

1.739 × 10^{-9} m^2/s for the samples pretreated with potassium carbonate, 5.218×10^{-10} and 1.300×10^{-9} m^2/s for the specimens pretreated with the blanching method, and finally 4.886×10^{-10} and 1.292×10^{-9} m^2/s for the samples pretreated with citric acid and ascorbic acid mixture solution.

The results of the studies showed that the effective diffusivity coefficients obtained in this study were found to be consistent with the generally accepted values obtained in previous studies (Zogzas *et al.*, 1996), changing between 10^{-12} and 10^{-8} m^2/s. The values of D_{eff} obtained in this study are comparable with the reported values of 2.27-4.97×10^{-10} m^2/s for organic apple slices (Sacilik and Elicin, 2006), 2.93-6.08×10^{-10} m^2/s for Amasya apple slices (Doymaz, 2010), and 7.03-10.8×10^{-10} m^2/s apple slices (Beigi, 2016b).

It was thought that the diffusion coefficients used in previous studies were different from the values of this study because of the difference of the apple type used in the experiments, the difference of the drying air velocity and the difference of the pretreatment method used and the self-life. Other factors that may also have discrepancies include drying temperature and the type of dryer used.

The Eq. (8) was used in the calculation of the activation energy required for drying of apple slices. The activation energy was calculated by plotting in $\ln(D_{eff})$ with respect to $1/(T + 273.15)$. The values of activation energy were calculated using the equations of the curves in the Fig. 8.

With the help of the following equations (Eqs. 11-14), it can be seen how the diffusion coefficients of the samples dried by pretreatment method and the control samples are affected by the temperature.

Potassium Carbonate

$$D_{eff} = 3.981 \times 10^{-4}\exp\left(-\frac{4337.3}{(T+273.15)}\right) \quad R^2 = 0.9537 \quad (11)$$

Citric Acid and Ascorbic Acid

$$D_{eff} = 3.095 \times 10^{-4}\exp\left(-\frac{3911.9}{(T+273.15)}\right) \quad R^2 = 0.9728 \quad (12)$$

Blanching

$$D_{eff} = 3.293 \times 10^{-4}\exp\left(-\frac{3587.8}{(T+273.15)}\right) \quad R^2 = 0.9767 \quad (13)$$

Control

$$D_{eff} = 3.027 \times 10^{-4}\exp\left(-\frac{3860.2}{(T+273.15)}\right) \quad R^2 = 0.9865 \quad (14)$$

The activation energy values of the samples dried in the cabinet dryer, also pretreated with potassium carbonate, citric acid and ascorbic acid mixture, blanching method and control group without pretreatment were found to be 36.1, 32.5, 29.8 and 32.1 kJ/mol, respectively. These values are similar to those proposed in the literature for apple slices drying: 14.47-22.06 kJ/mol (Doymaz, 2010); 17.77-25.41 kJ/mol (Beigi, 2016a), and 19.95–22.62 kJ/mol in delicious apple drying (Kaya *et al*., 2007). The value of activation energy was within the general range of 15–40 kJ/mol for various food materials (Rizvi, 1986).

IV. CONCLUSIONS

The effect of air temperature and pretreatment on drying characteristics of apple was investigated in the cabinet dryer. Constant drying rate period was not observed, the drying process took place in the falling-rate period. Drying data obtained were fitted to five thin-layer drying models and goodness of fit determined using R^2, χ^2 and $RMSE$. The Midilli & Kucuk model gave the best representation of drying data under all experimental conditions. The effective moisture diffusivity was computed from Fick's second law, the values of which varied between 4.804×10^{-10} m^2/s and 1.739×10^{-9} m^2/s, over the temperature range. The effective moisture diffusivity increases as temperature increases. The relationship between the effective moisture diffusivity and temperature can be described by Arrhenius-type relationship. The values of activation energy were in the range 29.8-36.1 kJ/mol.

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