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Investigating of drying kinetics and mathematical modeling of turnip

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Abstract: The drying process of turnip and drying rate curves were investigated at different temperatures (55, 70 and 85°C) with air flow rate of 1.5 m/s. Also effective diffusion coefficient and activation energy were calculated by using Arrhenius equation and Fick's second law for infinite slab. The effective diffusivity varied between 5.471×10^{-10} and 8.966×10^{-10} in the range of (55°C to 85°C). The value of activation energy was found to be 16.013 kJ/mol. The mathematical models (Newton, Page, Modified Page, Henderson and Pabis, Logarithmic, Two term, Two term exponential, Wang and Singh, Simplified Fick's diffusion, Modified Page –II, Verma, Midilli–Kucuk, Hii, Law and Cloke, Approximation of diffusion, Modified Henderson and Pabis) were fitted to the experimental data. Sigmaplot v10.0 software was used to find the best model for evaluating the rate of moisture change. Decency of fit by these models was based on comparing the coefficient of determination (R^2), reduced chi-square (χ^2), mean bias error (MBE) and root mean square error (RMSE) between the observed and predicted variables. Among 15 evaluated models, Modified Henderson and Pabis in 85°C and Hii, Law and Cloke in 55°C and 70°C with highest R^2 and lowest MBE, χ^2 and RMSE were selected to better estimate the drying curves.

Keywords: Turnip, hot air convective drying, modeling, drying rate, effective diffusivity, activation energy

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1 Introduction

Brassica vegetables belong to *brassicaceae* family and include a variety of economically significant horticultural crops. They are an excellent source of antioxidants and also have anticancer properties (Van Poppel at al., 1999). Turnip, kale; broccoli and cabbage are among the most prevalently consumed species (Sikora et al., 2008). Brassica genus has been intensively studied due to its health benefits. Brassica rapa var. rapa L., commonly known as turnip, is one of the oldest cultivated vegetables (Takuno et al., 2007). It is a very popular crop for its edible or valuable parts (swollen roots, fleshy leaves, and more recently sprouts), being consumed in huge quantities all over the world (Takuno et al., 2007). Before the potato was introduced in Europe, the turnip was an important vegetable which provided a reliable source of food at times when other vegetables were scarce (Bradshaw, 2010). Different varieties of vegetables have been produced in Iran because

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of its appropriate and diverse climate. Iran exported some of produced turnips to other countries. Its monetary value in 2010 was about 3080652 US$ (Foreign trade statistics yearbook of Islamic republic of Iran, 2010). This species is particularly popular in Europe, particularly in its colder regions (Fernandes et al., 2007). The turnip, like table beet, was also a vegetable grown by the Romans, and most likely the Greeks before (Bradshaw, 2010). It grows well in cold climates and can be stored several months after harvest (Fernandes et al., 2007). Antioxidants are responsible for the control of Free radicals that can cause cancer in human beings. Dietary antioxidants present in these vegetables, like water-soluble vitamin C and phenolic compounds, as well as lipid-soluble vitamin E and carotenoids, can act against oxidative stress (Lampi et al., 2002; Czeczot, 2000; Davey et al., 2000). In conclusion, they might protect humans from chronic diseases, such as cancer and cardiovascular disease (Podsedek et al., 2006; Cartea and Velasco, 2008; Traka and Mithen, 2009). Turnip is a valuable source for Calcium and magnesium salts that are important in the prevention of dangerous diseases like cancer. Also it is a major source of fiber (Vogl-Lukasser et al., 2009). Fiber can provide many health benefits such as, lowering cholesterol, risk of diabetes and heart disease, normalizing and regulating bowel function, aids in weight loss, and prevention of colon cancer. A group of chemical compounds called glucosinolates that are effective in preventing cancer have found in Brassica families. According to research studies, these compounds have the power to stop the spread of cancer in laboratory animals. With respect to Laboratory analysis about 39-166 mg glucosinolates are founded in every hundred grams of raw turnip greens (Podsedek, 2007).

Not only large amounts of calcium are in turnip greens, but also, this plant contains large amounts of iron and copper that result in increasing the level of blood hemoglobin. Also being various vitamins like A, B and C in the leaves and roots clearly indicating its important role in maintaining the neural and nutritional balance. Given that, turnip roots and leaves contain a large amount of vitamin C and Beta-Carotene respectively; so, this plant can be used in the treatment of respiratory diseases, especially colds (Vogl-Lukasser et al., 2009). Drying is defined as a process of moisture removal due to simultaneous heat and mass transfer. The objective of food drying is the long-term storage of food, and minimizing the costs of transportation, storage and packaging. Drying operation has a huge impact on quality and price of food products. Food quality depends on the physical and biochemical changes that occur during the drying process. Drying time, temperature and water activity have a considerable effect on the food quality (Mujumdar and law, 2010). Hot air drying is one of the most common methods to preserve foods. By reducing water activity, preventing the growth of microorganisms and minimizing the destructive reactions, it can increase food shelf life (Vega-Mercado et al., 2001). In 2008, Basavaraj et al. dried figs with hot air at temperatures 55°C, 65°C, 75°C. According to their results, drying of figs that occurred in the descending phase and high temperatures caused a drop in quality properties such as color, odor, and flavor. Drying of various products such as potato, pistachio, apricot, banana, green bean and onion, grape, carrot, kale and eggplant has been studied by following researchers respectively (Akpınar et al., 2003; Midilli and Kucuk, 2003; Togrul and Pehlivan, 2003; Dandamrongrak et al., 2002; Yaldız and Ertekin, 2001; Pangavhane et al., 1999; Doymaz, 2004; Mwithiga and Olwal, 2005; Ertekin and Yaldiz, 2004). By modeling, the drying process can be predicted. In other words, by selecting the best model to describe the drying kinetics, nutrient changes during the drying process can be examined. And appropriate industrial dryers can be designed according to the type of food. Because of low dispersion and uniform data, in most studies, the drying kinetics model is based on the obtained relative humidity. The aim of this study was to study the effect of air temperature on the drying process and drying rate curve in different temperatures (55°C, 70°C and 85°C). Also effective diffusion coefficient and activation energy were calculated by using Arrhenius equation and Fick's second law for infinite slab. Moreover, development of a mathematical model for drying of turnip, selecting an appropriate model, investigation of the effects of drying air temperature and velocity on the model coefficients that can describe the drying characteristics of turnip were investigated.

2 Materials and methods

2.1 The laboratory dryer

The drying experiments carried out at three hot air temperatures 55°C, 70°C and 85°C in a fan tray dryer (model UNE 400 PA, Memmert, Scheabach, Germany) in the food science Department, University of Sabzevar, Iran, that could be regulated to any preferred drying air temperature between 20°C and 120°C and velocity between 0.1 and 3.0 m/s with remarkable accuracy. Weighing of samples inside the drying chamber was done manually using a digital scale with the accuracy of 0.01 g. Weighing the samples was continued until reaching equilibrium moisture content (Gikuru and Olwal, 2005).

2.2 Methods

Samples were sorted according to their color and size. Also physically damaged ones were separated from others. According to Iran's national standard (number 451), samples were transported in a polyethylene packages and refrigerated at 4°C. Before the drying process, turnips were washed and peeled, then cut to cube slices (10×10×5 mm) with thickness of 5 mm by cutting machine. Moisture content of the samples was determined by means of oven method at 105°C for 24 h with three replicates (AOAC, 1997). The initial moisture content of the slices was calculated to be 88.51% as an average of the obtained results.

2.3 Mathematical modeling of drying curves

In order to select an appropriate model for describing the drying process of turnip slices, drying curves were fitted with 15 well-known equations (Table 1). Regression analysis based on the independent variable was solved by software Sigmaplot 10. The coefficient of determination R^2 was one of the major criteria for choosing the proper equation. Moreover, decency of fit by these models was based on comparing the coefficient of determination (R^2), reduced chi-square (χ^2), mean bias error (MBE) and root mean square error (RMSE) between the observed and predicted variables. The equations with highest $\mathbf{R}^2$ and lowest MBE and RMSE were chosen to better estimate the drying curves (Goyal et al., 2008; Doymaz, 2007; Arumuganathan, 2009; Togrul and Pehlivan, 2003; Ibrahim et al., 2009). Table 1 shows experimental models of hot air drying that were used in this study.

Table 1 Mathematical models applied to drying curves of turnip samples

No	Model name	Equation	References
1	Newton	$MR = \exp(-kt)$	(Liu and Bakker-Arkema, 1997)
2	Page	$MR = \exp(-ktn)$	(Zhang and Litchfield, 1991)
3	Modified Page	$MR = \exp(-(kt)n)$	(Overhults et al., 1973)
4	Henderson and Pabis	$MR = a\exp(-kt)$	(Henderson and Pabis, 1961 and Chhinnman, 1984)
5	Logarithmic	$MR = a\exp(-kt) + c$	(Yagcioglu et al., 1999 and Yaldiz et al, 2001)
6	Two term	$MR = a\exp(-k_o t) + b\exp(-k_1 t)$	(Henderson, 1974)
7	Two term exponentia	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	(Sharaf-Eldeen et al., 1980)
8	Wang and Singh	$MR = 1+ at + bt^2$	(Wang and Singh, 1978)
9	Simplified Fick's diffusion	$MR = a\exp(-c(t/l^2))$	(Diamante and Munro, 1993)
10	Modified Page –II	$MR = \exp(-c(t/l^2))^n)$	(Diamante and Munro,1993)
11	Verma	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	(Verma et al., 1985)
12	Midilli–Kucuk	$MR = a\exp(-ktn) + bt$	(Midilli et al., 2002)
13	Hii, Law and Cloke	$MR = a\exp(-ktn) + c\exp(-gtn)$	(Hii et al., 2009)
14	Approximation of diffusion	$MR = a\exp(-kt)+(1-a)\exp(-k\,at)$	(Yaldiz et al., 2001)
15	Modified Henderson and Pabis	$MR = a \times \exp(-kt) + b \times \exp(-gt) + c \times \exp(-ht)$	(Karathanos, 1999)

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,avg})^2}{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{\exp,avg})^2} \quad (1)$$

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

$$\chi^2 = \frac{\sum_{i=1}^{n}(MR_{\exp,i} - MR_{pre,i})^2}{N-n} \quad (3)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i}) \quad (4)$$

where, $MR_{\exp,i}$ is the experimental moisture ratio; $MR_{\text{pre},i}$ is the predicted moisture ratio; N is the number of observation and z is the number of constants (Sharma et al., 2005; Kumar et al., 2011; Arumuganathan et al., 2009; Togrul and Pehlivan, 2003; Rayaguru and Routray, 2011).

2.4 Calculation of moisture on the wet base

From Equation (6) the amount of moisture on the basis of wet base was calculated during the drying process.

$$M_0 \times X_{s0} = M_t \times X_{st} \quad (5)$$

$$1 - X_{st} = X_{wbt} \quad (6)$$

where, M_0 is the initial moisture content (kg water/kg dry solid); M_t is the moisture content at any time (kg water/kg dry solid); X_{s0}, X_{st} initial and final solid contents of a sample (g) and X_{wbt} is the amount of moisture on the wet base (Tavakolipour, 2009).

2.5 Calculation of moisture content on the dry base

From Equation (7) the amount of moisture on the basis of dry base was calculated during the drying process.

$$X_{db} = \frac{X_{wb}}{1 - X_{wb}} \quad (7)$$

where, X_{db} (kg water/kg dry matter) is the amount of moisture in the dry base and X_{wb} (kg water/kg total matter) is the amount of water in the wet base (Tavakolipour, 2009).

2.6 Calculation of drying rate

The drying rate (DR) of turnip slices was calculated using Equation (8):

$$DR = \frac{MC_{t+dt} - MC_t}{\Delta t} \quad (8)$$

where, MC_{t+dt} is moisture content at $t+d_t$ (kg water/kg dry matter); MC_t is moisture content at td_t (kg water/kg dry matter); and t is the drying time (min) (Al-Harahsheh et al., 2009; Wong, 2001).

2.9 Drying kinetic and determination of effective diffusivities

It has been accepted that drying curve was in falling rate period, so diffusion model was used to analyze the drying process. Meanwhile turnip samples are assumed to be infinite slab.

$$MR = \frac{(X - X_e)}{(X_0 - X_e)} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\left(\frac{\pi^2 D_{eff} t}{4L^2}\right)\right] \quad (9)$$

where, D_{eff} is the effective diffusivity (m^2/s); L_0 is the half thickness of slab (m); X_e is the equilibrium moisture content; x_0 is the initial moisture content of sample; x is the amount of moisture on the basis of dry base; t is the required time for sampling and MR is a moisture ratio. The half thickness of slab (m) was assumed to be constant. It should be considered that in the Equation (9) 'n', was assumed to be zero, therefore the above equation can be converted to Equation (10). For long drying period, Equation (10) can be simplified. It means, Equation (10) can be written in a logarithmic form as follows.

$$\ln MR = \ln\frac{(X - X_e)}{(X_0 - X_e)} = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4L^2}\cdot t \quad (10)$$

Diffusivities are usually calculated by plotting experimental drying data in relation to lnMR versus drying time t in Equation (11), since the plot provides a straight line with a slope as follows:

$$D_{eff} = \frac{4L^2 K_1}{\pi^2} \quad (11)$$

2.10 Calculation of activation energy

According to dependence of the effective diffusivity with temperature activation energy was calculated by using Arrhenius relationship (Falade et al., 2007; Arumuganathan et al., 2009).

$$D_{eff} = D_0 \exp\left(\frac{E_a}{R}\right)\cdot\frac{1}{T} \quad (12)$$

where, D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s); E_a is the activation energy (kJ/mol); R is the universal gas constant (kJ/mol K), and T is the temperature (K).

Equation (13) can be written in a logarithmic form like follows:

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{R}\left(\frac{1}{T}\right) \quad (13)$$

Plotting lnD_{eff} versus $1/T$ gives straight line with the slope of K_2 (Equation (14)) as follows.

$$K_2 = \frac{E_a}{R} \tag{14}$$

3 Results and discussion

3.1 Influence of air temperature

The effect of three temperatures on the drying curve of turnip is shown in Figure 1.

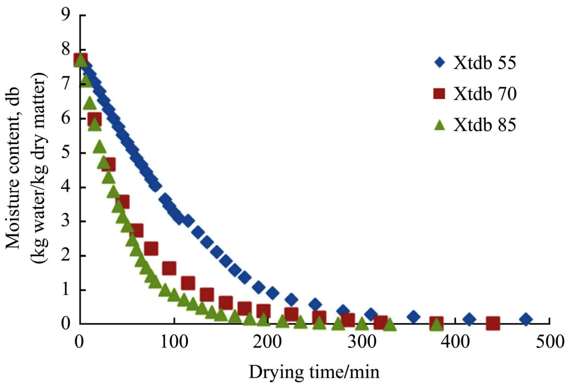

Figure 1 Moisture content changes in dry basis during drying

The slope of this curve shows that, the use of higher temperatures cause rapid evaporation of moisture of turnip samples that result in rapid access to equilibrium moisture. It is apparent from Figure 1 that increasing the drying temperature caused a significant decrease in the drying time. The turnip slice of initial moisture content of about 7.70 kg water per kg dry matter was dried to the final moisture content of about 0.0079 kg water per kg dry matter till no further changes in their mass were observed. According to results of our study, it can be found that the drying time was longest at 55°C, and shortest at 85°C. To reach optimum final moisture content, the drying time was 475 min at 55°C, 440 min at 70°C and 380 min at 85°C. These results indicate that, the drying time decreased by 7.36% and 13.36% respectively, so the drying time did not illustrate equal decrease with the temperature increasing at equal interval. The increased temperature interval of 15°C from 70°C to 85°C has better effect on the decreasing drying time. Reduction of humidity in the given temperatures follows fitted regressions in Table 2.

Similar findings were reported by Doymaz (2004) for okra, Doymaz and Pala (2002) for pepper, Johnson et al. (1998) for banana, Mwithiga and Olwal (2005) for kale, Menges and Ertekin (2006) for golden apple, Doymaz (2004) for carrot, Togrul and Pehlivan (2002) for apricots drying. All of their reports have stated that the increase in temperature, leads to decreasing the drying time. This is due to high temperatures accelerate the moisture removal from the surface in comparison to the low temperatures.

Table 2 Regression equations for change of humidity in dry base in selected temperature, °C

Temperatures, °C	Regression Equation	R^2
55	$y=8.332e^{-0.01x}$	0.981
70	$y=6.950e^{-0.01x}$	0.990
85	$y=6.920e^{-0.02x}$	0.992

3.2 Drying rate curve

Drying rate is described as the amount of water removed from samples as a function of time. Drying rate decreases continuously with decreasing moisture content or improving drying time. Figure 2 shows that, increasing the air temperature increases the drying rate, and decreases drying time. So it is obvious that drying rate decreases constantly with increasing drying time. The experimental results indicated that air temperature is considered as the main factor affecting drying rate because the movement of moisture to surface and evaporation rate from surface to air decrease with reduction of the moisture in our samples, therefore the drying rate noticeably decrease. It means a higher drying air temperature produced a higher drying rate and accordingly the drying time declined. This is due to the rise of heat transfer between the air and the turnip, and the moving up of water from inside of them. According to mentioned analysis, the rate of turnip drying increased compared to other temperatures, at 85°C.

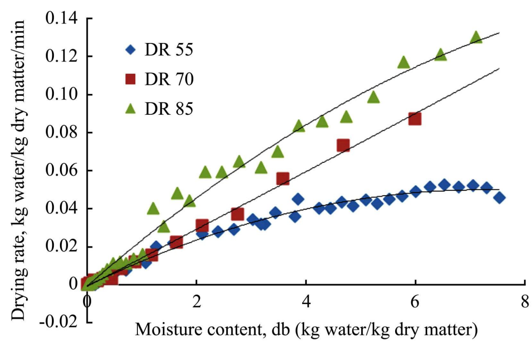

Figure 2 Drying rate versus moisture content of turnip samples at different temperatures

Figure 2 shows that, the maximum drying rates for drying turnip slabs were 0.0456, 0.0874 and 0.1304 g water/g dry matter/min at temperatures of 55°C, 70°C and 85°C respectively. It was also perceived that the drying rates were higher at higher drying temperatures. The average drying rate increased by 91.66% and 49.2% at each identical temperature interval of 15°C from 55°C to 85°C.

Data in Table 3 shows regression analysis of drying rate on the basis of moisture content of dry base (mc_{db}).

Table 3 Regression equations of drying rate for Moisture content, db in selected temperature, °C

Temperatures, °C	Regression Equation	R^2
55	y=-0.00096x^2+ 0.01396x−0.00059	0.98104
70	y=-0.00003x^2+ 0.01499x−0.00091	0.99503
85	y=-0.00100x^2+ 0.02521x−0.00078	0.98624

It was noted that, there was no constant drying rate during drying of turnip samples.

It should be mentioned that, values of R^2 in the Table 3 shows high experimental accuracy. These results were in agreement with some other studies in this regard. (Prasad and Sharma, 2001; Yaldiz and Ertekin, 2001; Babalis and Belessiotis, 2004; Doymaz, 2005; Gazor and Mohsenimanesh, 2010; Zielinska et al., 2010; Promvonge et al., 2011).

3.3 Calculation of moisture diffusivity and activation energy

Drying of most foods occurs in the falling rate periods and internal mass transfer resistance controls the drying time. Fick's second law can be used to illustrate the drying behavior for the majority of biological materials as follows:

$$\frac{\partial \phi}{\partial t} = D\frac{\partial^2 \phi}{\partial x^2} \tag{15}$$

where, ϕ is the moisture concentration; t is the time; x is the distance from the centerline of a symmetrical sample in the direction of moisture flow, and D the diffusion coefficient. On the basis of the assumptions of uniform initial moisture distribution, minor external resistance, negligible temperature gradients, and negligible shrinkage during drying, and steady diffusion coefficient, the analytical solution of the diffusion equations can be written for is given as follows

$$\ln MR = \ln\frac{(X - X_e)}{(X_0 - X_e)} = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4L^2}\cdot t \tag{16}$$

It should be considered that turnip samples are assumed to be infinite slab. Where D_{eff} is the effective diffusivity representing the conductive term of all moisture transfer mechanisms (m^2/s); L_0 is the half thickness of slab (m). x_e is the equilibrium moisture content; x_0 is the initial moisture content of sample; x is the amount of moisture on the basis of dry base; t is the required time for sampling and MR is a moisture ratio. The half thickness of slab (m) has been assumed to be constant. It should be considered that in Equation (9) n, equaled to zero, therefore the above equation can be converted to Equation (10). For long drying period, Equation (10) can be simplified. It means, Equation (10) can be written in a logarithmic form as follows. Diffusivities are usually calculated by plotting experimental drying data in relation to lnMR versus drying time t in Equation (10), since the plot provides a straight line with a slope as follows:

$$D_{eff} = \frac{4L^2 K_1}{\pi^2}$$

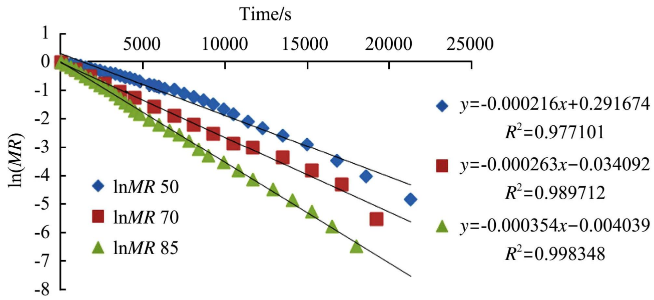

Figure 3 Variation of moisture ratio with drying time at selected temperatures

The determined values of D_{eff} for given temperatures were found 5.47×10^{-10}, 6.66×10^{-10} and 8.96×10^{-10} m^2/s at 55°C, 70°C and 85°C, respectively. The minor variances among values could be due to the differences in varieties, drying equipment and other uncontrolled parameters. The effective diffusivity increased with the increase of the drying air temperatures. Studies indicate that proper coordination between obtained effective diffusivities with the results of other researchers like Lee and Kim (2009) for white radish, Doymaz (2007) for tomato, Arslan and Özcan (2010) for onion, Pardeshi et al. (2009) for green pea, and Kolawole et al. (2010) for pepper. All these data were in the range of our results. Activation energy is the energy required to begin mass diffusion in foods (Ayim et al., 2012).

The dependence of the effective diffusivity with temperature activation energy was calculated by using Arrhenius relationship (Falade et al., 2007; Arumuganathan et al., 2009).

$$D_{eff} = D_0 \exp\frac{E_a}{R} \cdot \frac{1}{T} \tag{17}$$

where, D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s); E_a is the activation energy (kJ/mol); R is the universal gas constant (kJ/mol K), and T is the temperature (K). Equation (3) can be written in a logarithmic form like follows:

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{R} \cdot \left(\frac{1}{T}\right) \tag{18}$$

Plotting $\ln D_{eff}$ versus $1/T$ gives straight line with the slope of K_2 (Equation (14)) as follows.

$$K_2 = \frac{E_a}{R} \tag{19}$$

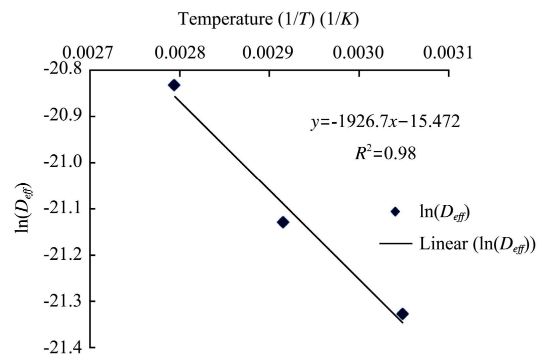

Figure 4 The Arrhenius type relationship between effective diffusivity and drying temperature

According to calculations E_a and pre-exponential factor were determined to 16.013 kJ/mol and 1.912×10^{-7} m/s^2. Our value is consistent with the present results of other researchers. Activation energy for various fruits and vegetables is shown in Table 4.

Table 4 Activation energies of various products

Product	E_a, kJ/mol	References
Apple	19.96	(Kaya et al., 2007)
Red chili	24.47	(Kaleemullah and Kailappan, 2007)
Lettuce	19.82	(Lopez et al., 2000)
Potato	23.20	(Doymaz, 2011)
Radish	16.49	(Lee and Kim, 2009)
Green pea	22.48	(Pardeshi et al., 2009)
Tomato	17.55	(Kamil, 2007)
Potato	20	(Bon et al., 1997)

3.4 Evaluation of the models

In the analysis of drying data, the MR kinetics is fundamental to explain the drying process of turnip samples. The values of coefficient of determination, mean bias error, root mean square error and reduced chi-square with estimated parameters for the 15 models are shown in Table 5.

Table 5 Results of statistical analyses on the modeling of moisture contents and drying time

MBE	χ^2	RMSE	R^2	T, °C	models
-1.107×10^{-3}	1.4383×10^{-3}	0.0374	0.9861	55	Newton
-1.8644×10^{-3}	5.1118×10^{-5}	6.95×10^{-3}	0.9994	70	
-1.1×10^{-4}	2.2672×10^{-4}	0.0148	0.9975	85	
2.3065×10^{-3}	1.5489×10^{-4}	0.0121	0.9985	55	Page
-1.1389×10^{-3}	3.8687×10^{-5}	5.8642×10^{-3}	0.9996	70	
-1.2609×10^{-3}	5.8312×10^{-5}	7.4083×10^{-3}	0.9994	85	
2.3065×10^{-3}	1.5488×10^{-4}	0.0121	0.9985	55	Modified Page
-1.1389×10^{-3}	3.8687×10^{-5}	5.8642×10^{-3}	0.9996	70	
-1.2609×10^{-3}	5.8312×10^{-5}	7.4083×10^{-3}	0.9994	85	
6.1189×10^{-3}	8.6611×10^{-4}	0.0286	0.9919	55	Henderson and Pabis
-2.0428×10^{-3}	5.2812×10^{-5}	6.8516×10^{-3}	0.9994	70	
1.3743×10^{-3}	1.5081×10^{-4}	0.0119	0.9984	85	
-1.0540×10^{-5}	4.815×10^{-4}	0.021	0.9956	55	Logarithmic
3.2222×10^{-6}	4.12×10^{-5}	5.8595×10^{-3}	0.9996	70	
3.147×10^{-6}	1.488×10^{-4}	0.0117	0.9984	85	
1.3643×10^{-3}	1.6421×10^{-4}	0.012	0.9985	55	Two term
3.2078×10^{-4}	2.7507×10^{-5}	4.6254×10^{-3}	0.9997	70	
-9.797×10^{-4}	5.5833×10^{-5}	7.0189×10^{-3}	0.9994	85	
2.3107×10^{-3}	1.7989×10^{-4}	0.013	0.9983	55	Two term exponential
-1.9889×10^{-4}	2.5687×10^{-5}	4.7784×10^{-3}	0.9997	70	
-1.64×10^{-3}	$5,7187\times10^{-5}$	7.3364×10^{-3}	0.9994	85	
6.9934×10^{-3}	1.458×10^{-3}	0.0371	0.9863	55	Wang and Singh
0.0438	0.0209	0.1364	0.7759	70	
0.049	0.0222	0.1447	0.7601	85	
6.12×10^{-3}	8.9159×10^{-4}	0.02862	0.9919	55	Simplified Fick’s diffusion
-2.0372×10^{-3}	5.6287×10^{-5}	6.8488×10^{-3}	0.9994	70	
1.3743×10^{-3}	1.5568×10^{-4}	0.0119	0.9984	85	
1.1070×10^{-3}	1.52298×10^{-3}	0.0374	0.9861	55	Modified Page –II
-1.8644×10^{-3}	5.7933×10^{-5}	6.9482×10^{-3}	0.9994	70	
-1.1×10^{-4}	2.4136×10^{-4}	0.0148	0.9975	85	
1.7718×10^{-3}	1.5782×10^{-4}	0.012	0.9986	55	Verma
6.1167×10^{-5}	2.6667×10^{-5}	4.714×10^{-3}	0.9997	70	
-9.6705×10^{-4}	5.3903×10^{-5}	7.0104×10^{-3}	0.9994	85	
-0.0266	1.397×10^{-4}	0.0112	0.9988	55	Midilli–Kuc uk
-3.0834×10^{-4}	4.1086×10^{-5}	5.653×10^{-3}	0.9996	70	
-2.9794×10^{-4}	5.8×10^{-5}	7.1538×10^{-3}	0.9994	85	
5.7837×10^{-6}	1.1834×10^{-4}	0.0101	0.999	55	Hii, Law and Cloke
3.0322×10^{-4}	2.1308×10^{-5}	3.9229×10^{-3}	0.9998	70	
1.2932×10^{-4}	5.2897×10^{-5}	6.717×10^{-3}	0.9995	85	
1.8029×10^{-3}	1.5891×10^{-4}	0.012	0.9986	55	Approximati on of diffusion
6.0945×10^{-5}	2.667×10^{-5}	4.714×10^{-3}	0.9997	70	
-9.6705×10^{-4}	5.3903×10^{-5}	6.8965×10^{-3}	0.9994	85	
4.0673×10^{-4}	1.3103×10^{-4}	0.0104	0.9989	55	Modified Henderson and Pabis
4.3295×10^{-4}	2.592×10^{-5}	4.1567×10^{-3}	0.9998	70	
2.6059×10^{-5}	4.8714×10^{-5}	6.3338×10^{-3}	0.9995	85	

According to evaluated criteria that are listed in the Table 4 it can be seen that, Hii, Law and Cloke at 55°C and 70°C and Modified Henderson and Pabis at 85°C models fitted better than other models on the basis of R^2, χ^2, MBE and RMSE. It means these models can be used for hot air drying of turnips at the recommended temperatures. For all experiments coefficient of determination (R^2) was higher than 0.988 and the amount of R^2, RMSE, χ^2, and MBE at 55°C for Hii, Law and Cloke model was 0.9990, 0.0101, 1.1834×10^{-4} and 5.7837×10^{-6} respectively. These values at 70°C were 0.9998, 3.9229×10^{-3}, 2.1308×10^{-5} and 3.0322×10^{-4} respectively also for Modified Henderson and Pabis at 85°C were 0.9995, 6.3338×10^{-3}, 4.8714×10^{-5} and 2.6059×10^{-5} respectively.

Similar researches have been done to model the drying kinetics of some food samples such as carrot pomace (Kumar et al., 2010), red bell pepper (Vega et al., 2001), apple pomace (Wang et al., 2007), Eggplant (Ertekin and Yaldiz, 2004), tomatoes (Kamil, 2007; Doymaz, 2007). The following charts show comparison between the experimental and calculated moisture ratio of best models of turnip samples at selected drying temperatures (55°C, 70°C, 85°C).

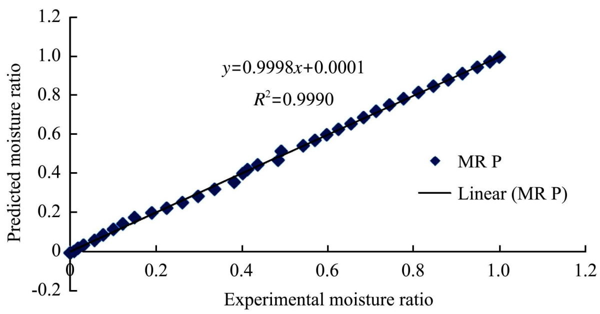

Figure 5 Experimental and predicted moisture ratio values for the Hii, Law and Cloke model at 55°C

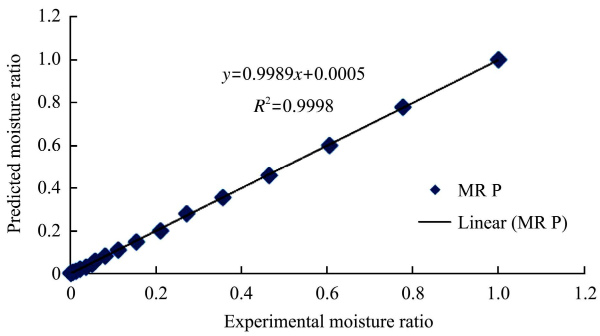

Figure 6 Experimental and predicted moisture ratio values for the Hii, Law and Cloke model at 70°C

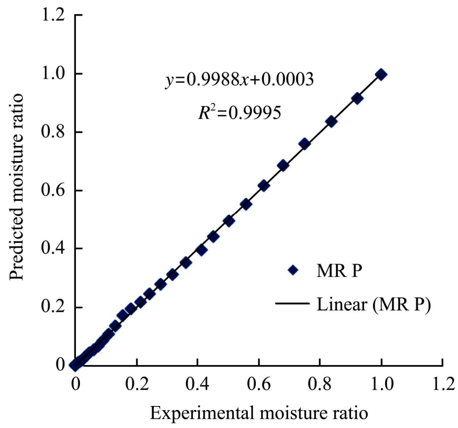

Figure 7 Experimental and predicted moisture ratio values for the Modified Henderson and Pabis model at 85°C

According to diagrams, very good conformity between calculated and experimental data can be seen, on the other hand, for all diagrams the value of (R^2) was higher than 0.9. It means the selected models could satisfactorily explain the drying behavior of turnip samples.

4 Conclusions

The drying characteristics during hot air drying of turnip samples were measured at three different temperatures. The following consequences can be drawn based on the results achieved in this work:

1) The drying characteristics of the turnip samples were studied in a convective hot air dryer as cube slices (10×10×5 mm) with thickness of 5 mm at the drying air temperatures of 55°C, 70°C and 85°C. The moisture content and drying rate were affected by the drying air temperature. Increasing of the drying air temperature led to reduction of the drying time and increasing of the drying rate.

2) Effective diffusivity increased with increased of temperature. The temperature dependence of the effective diffusivity was also described by the Arrhenius relationship. The activation energy for moisture diffusion was 16.013 kJ/mol.

3) Four statistical tools were used to compute the goodness of fitting and change of moisture ratio with time, the determination of coefficient (R^2), the reduced chi-square (χ^2), mean bias error (MBE) and root mean square error (RMSE). Among 15 evaluated models, Modified Henderson and Pabis in 85°C and Hii, Law and

Cloke in 55°C and 70°C, with highest R^2 and lowest MBE, χ^2 and RMSE, were considered the best models to explain the drying characteristics of turnip samples. It means these models are appropriate to apply for prediction of water loss during drying and for better controlling the process and high quality production.

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