GIDA (2011) 36 (4): 201-208 *Research* / Araştırma

EFFECTIVE MOISTURE DIFFUSIVITY AND DRYING CHARACTERISTICS OF TOMATO SLICES DURING CONVECTIONAL DRYING

Ö. Faruk Gamlı[1]

Department of Food Technology,
Korkut Ata University, Vocational High School of Bahçe, Bahçe-Osmaniye, Turkey

Received / Geliş tarihi: 23.05.2011
Received in revised form / Düzeltilerek geliş tarihi: 05.07.2011
Accepted / Kabul tarihi: 14.07.2011

Abstract

The drying characteristics of the tomato slices were investigated at 65, 70, 75 and 80 °C. The tomato samples were dried up to 2-3 % wet basis (w.b). The experimental data of the tomato samples were fitted to the six models; Page's, Henderson & Pabis, Logaritmic, Wang & Sing, Midilli and Polynommial model. SSE, R^2 and RMSE % values were used to determine the suitability of these models for describing the drying curves of tomato slices. Polynommial model gave better results compared to others. Effective moisture diffusivity values (D_{eff}) were found between $5.86.10^{-9}$ and $2.505.10^{-8}$ m²/s for tomato slices and increasing drying temperature causes an increase in D_{eff} values. The activation energy was found as 24.92 kJ/ mole.

Keywords: Curve fittings, drying kinetics, moisture diffusivity, tomato slices, polynommial model

KONVEKSİYONAL KURUTMADA DOMATES DİLİMLERİNİN KURUTMA KARAKTERİSTİKLERİ VE EFEKTİF NEM YAYILIM DEĞERİ

Özet

Bu çalışmada, domates dilimlerinin 65, 70, 75 ve 80 °C'deki kurutma karakteristikleri araştırılmıştır. Domates numuneleri % 2-3 nem içeriğine kadar kurutulmuştur. Domates numunelerinin kurutma verileri, Page, Henderson & Pabis, Logaritmik, Wang & Sing, Midilli ve Polinom modelleri kullanılarak verilerin modellere uygunluğu denenmiştir. Domates dilimlerinin kurutma eğrilerinin modellere uygunluğunun belirlenmesinde SSE, R^2 ve % RMSE değerleri kullanılmıştır. Polinom modelinin matematiksel eşitlikler içerisinde en uygun model olduğu belirlenmiştir. Domates dilimlerinin efektif nem yayılım değerlerinin (D_{eff}) $5.86.10^{-9}$– $2.505.10^{-8}$ m²/s arasında değiştiği ve artan kurutma sıcaklığının D_{eff} değerlerinde artışa neden olduğu belirlenmiştir. Domates dilimlerinin aktivasyon enerjileri 24.92 kJ/ mol olarak bulunmuştur.

Anahtar kelimeler: Eğri uydurma, kurutma kinetiği, nem yayılımı, domates dilimleri, polinom modeli

---

* *Corresponding author* / Yazışmalardan sorumlu yazar ;
✉ farukg69@gmail.com ✆ (+90) 328 861 2282 🖷 (+90) 328 861 2658

INTRODUCTION

Tomato (*Lycopersicum esculentum*) is commonly produced vegetable in the world. It is grown worldwide on a variety of soils due to climatic conditions. United States, Turkey, Italy and Spain are the main tomato growing countries. Turkey produced 9440000 metric tons of tomato in 2004 (1). It is used to great extent in fresh juice, sauces, dried and paste forms. It is a good sources of macro minerals such as Na, K, Ca, Mg, P, S and micro minerals as Mn, Fe, Cu, Zn and Se meanwhile the carotenoid content of tomato varies between 132-583 µg/g dry weight. It is reported that carotenoid pigments are believed to help prevent cardiovascular disease, certain cancers and dietary lycopene is associated with reduced incidence of cardiovascular disease especially prostate cancer (2). Lycopene which is the predominat carotenoid pigment contributes to its red colour and helps in lowering DNA damage as an antioxidant (3); lycopene concentration varies between 6.0 and 15.0 mg/100 g for fresh tomato fruits and it's amount was affected by a number of factors such as high temperature, long processing time, light, oxygen and acids (4). Tomatoes also contain 5.60 % of dry matter, 0.47 % ash, 1.20 % glucose, 1.40 % fructose and 4.26 of pH values (5). Dried forms of tomatoes have many advantages including transportation, packaging and shelf-life of the product and it is preferred by soup producers (6). Tomato and its products are being used in many forms in Turkey. Many forms of tomatoes such as paste, sliced and whole forms are being dried in southern region in Turkey. Drying is one such thermal technique that offers an alternative way of preventing quality losses and increases commercial values of food materials. Drying of fruit and vegetables may result in physical, structural and nutritional changes such as case hardening, shrinkage and loss of volatile components and antioxidants. Some alternative drying methods like infrared drying, heat pump drying, osmotic dehydration and freeze drying are being used in practice (7, 10). It is reported that some fruits and vegetables are covered with a layer of wax that offers protection to the fruit or vegetables from external factors. The wax layer affects the flow of moisture from inside the fruit to its surface, a crucial process in drying procedure. Prior to drying process, chemical dipping in aqueous solutions of NaOH, NaCl and $CaCl_2$ overcomes the wax barrier on fruits or vegetables (8). Fruit and vegetables can be dried in different forms such as halves, slices and quarters during the drying process and it is reported that this process is a complex procedure in which heat and mass transfer phenomena contribute to moisture removal leading to substantial reduction in mass and volume product minimizing packaging, storage and transportation costs (9, 15). It is important to determine the drying parameters of drying process for the food materials that result in minimal change of quality parameters, we need to mathematical equations. There are several mathematical models are found for determining the drying parameters of the food materials such as Page's (10), Henderson & Pabis (11, 12), Wang & Sing (13), Midilli (14) , Weibull (15) and Logaritmic (16) models. Page's and Henderson & Pabis models for tomato (7, 10), Midilli equation for *Opuntia ficus indica* fruits (17) and Henderson & Pabis models are commonly used for drying kinetics of pine forest residue (18). The mathematical modelling allows the food researchers to choose the most suitable operating conditions either to describe the drying equipment or minimize the drying times for the final product specifications (15). Mathematical models will be achieved for drying characteristics of the tomato samples. Many studies considered based on the drying characteristics of tomatoes but few studies are found related with tomato slices.

The objective of this work was to examine the mathematical models for drying kinetics of tomato slices during convectional method. The fitting variables, effective moisture diffusivity (Deff) and activation energy (Ea) of tomato slices were determined.

MATERIALS AND METHODS

Materials

Fresh tomatoes (*Lycopersicum esculentum*) were purchased from a local market in Osmaniye, Turkey. Tomatoes were washed and then stored at 4 °C at refrigerator. Initial moisture content of samples were determined by using convectional method (7, 10, 11). Average moisture content was found as 94.38 % wet basis (w.b).

Methods

Drying Process

Drying procedures were done in a laboratory scale dryer in Food Technology Department. Tomatoes were washed in fresh water and sliced at a dimension of 4 mm thick and 80 mm diameter for drying procedure. Tomato slices were dried in triplicate forms and conducted at drying temperatures (65, 70, 75 and 80 °C) (Figure 1). Moisture loss was recorded at 15 min. time intervals during the drying process within an accuracy of 0.1 g. The drying process was carried out to final moisture content of 2-3 % from initial moisture content of about 94.38 % (w.b).

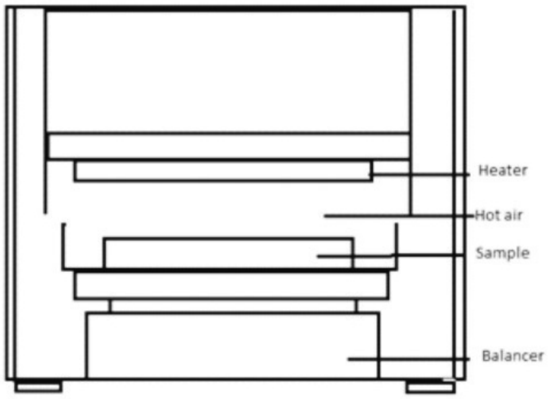

Figure 1. Drying equipment for tomato slice at 65-80 °C

Modelling of Drying Characteristics

There are some theoritical models describing drying kinetics for the food materials due to Fick's second equation. Supposing uniform initial moisture distribution, negligible external resistance, constant diffusivity and negligible shrinkage, the equation becomes

$$M_R=(M-M_e)/(M_o-M_e)=(8/\pi^2)\exp\{\pi^2 D_e/4L^2\} \quad (1)$$

where M is the moisture content at any times (kg water/kg dry solid), M_o is the initial moisture content of the sample (kg water/kg dry solid) and M_e is the equilibrium moisture content of sample (kg water/kg dry solid) (11).

Equation can be written in simplified form as (19, 20)

$$M_R=a \exp(-k.t) \quad (2)$$

where a and k are constants, t is drying times in minutes. k constant in equation (1) refers to

$$k= \pi^2 D_{ef} /4L^2 \quad (3)$$

and effective diffusivity (D_{eff}) can be obtained. D_{eff} values for the tomatoes increases with increasing the tempereatures and it varies between 2.3 and $9.1.10^{-9}$ m^2/ s for dried tomatoes from 60 to 110 °C (21); and changes between 3.72 and $12.27.10^{-9}$ m^2/ s for dried forms of tomatoes from 45 to 75 °C (22).

Page model has been used for drying characteristics of some fruit and vegetables such as pepper (23), apricot (24) and purslane (25).

$$M_R=\exp(-k.t^n) \quad (4)$$

where n is drying constant, t is time in minutes.

Logaritmic model is used widely for thin-layer drying process and it gives good fittings for olive cake (26) and roseship drying (27).

$$M_R= a.\exp(-k.t) + c \quad (5)$$

where a, k and c are constants, t is time in minutes.

Wang & Sing model developed by Wang & Sing (13) is

$$M_R= 1 + a.t +b.t^2$$

where a and b are constants, t is drying time in minutes.

Midilli equation is used for single type of drying for the food materials developed by Midilli et al. (14)

$$M_R= a.\exp(-k(t)^n)+ b.t \quad (7)$$

where a, k, n and b are constants, t is time in minutes.

Weibull equation is used for drying kinetics of the olive-waste cake (15).

$$M_R= \exp\{-(t/\beta)\alpha\} \quad (8)$$

where α is the shape parameter (dimensionless) and β is the scale parameter in minutes of the Weibull model.

A new mathematical model (polynommial) can be applied for the drying kinetsics of the tomato slices is

$$M_R = a.t^3 + b.t^2 + c.t + d \qquad (9)$$

where a, b, c and d are constants, t is time in minutes.

The effect of temperature on moisture diffusivity can be explained by Arrhenius equation which is

$$D_{eff} = D_o \exp\{-E_a/(R.T)\} \qquad (10)$$

where D_o is the pre-exponential factor for Arrhenius equation (m^2/s) and Ea is the activation energy for moisture diffusion (kJ/mole), R is the gas constant (kJ/mole.K) and T is the absolute temperature in K. The activation energy can be obtained by plotting the Ln D_{eff} versus the reciprocal of the temperature (1/T).

Statistical Analysis

The software package programme of Matlab (R200b) was used for the numerical calculations. There are several ways of determining suitability of the equations for the fittings procedures. The sum of square error (SSE), regression constant R^2 and root of mean square error (RMSE %) were used for the curve fitting procedure (8, 15, 28, 35).

RESULTS AND DISCUSSIONS

Modelling of Drying Kinetics of the Tomato Slices

The tomato slices were dried at different temperatures between 65 and 80 °C. Moisture ratios of the tomato slices were illustrated in Figure 2 and 3. As can be seen from the figures the moisture ratio decreases with increasing drying time. The moisture contents of the tomato samples were 94.38 % (w.b) at first and it decreased up to 0.03-0.04 level of moisture ratio. From the figures, it can be observed that the moisture ratio of tomato slices decreases with drying time and there is no constant rate period and drying process took place in the falling rate period. The rate of moisture removal from the product was higher at higher drying temperature and it is similar for coconut press cake (29), olive cake (26) and pomace of olive oil (31).

Several mathematical models are used for describing the drying curve of the food materials. Drying kinetics and curve fitting procedures of the tomato samples were examined by the models such as Page's, Henderson & Pabis, Wang & Sing, Logaritmic, Midilli, Weibull and Polynommial equations. Model constants and fitting parameters of the equations were given in Table 1. Acceptable R^2, SSE and RMSE % values were used for describing the suitability of the models. Among the models logaritmic model gave bad results due to R^2, SSE, and RMSE % values compared to other models. Constant k of the Page's model is the drying constant and characterizes the rate of moisture removal from the material per unit in time. The constants k and n varied between 0.001403 and 0.00163 and between 1.328 and 1.378 for tomato slices respectively.

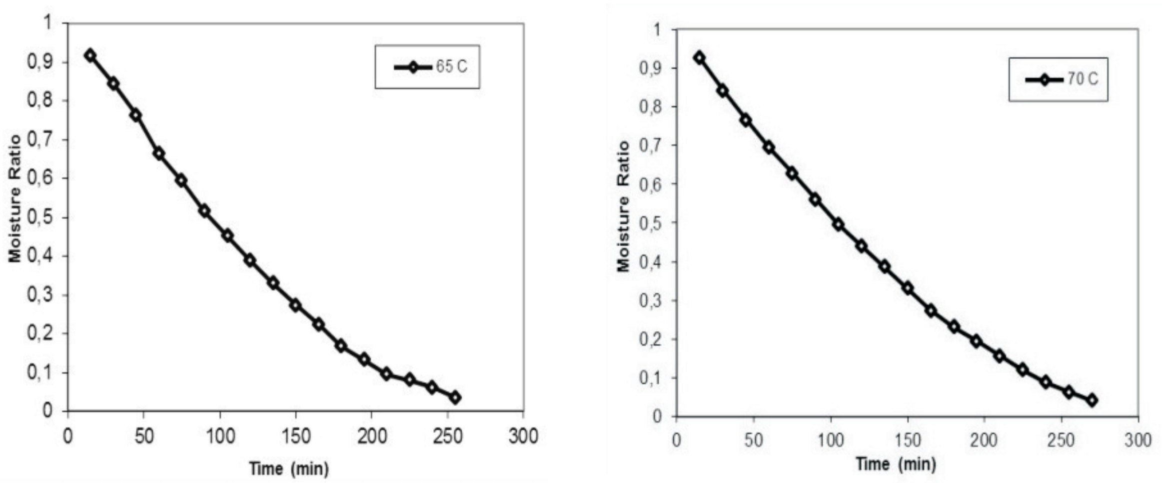

Figure 2. Variation of experimental moisture ratio of tomato slices with drying time at 65 and 70 °C.

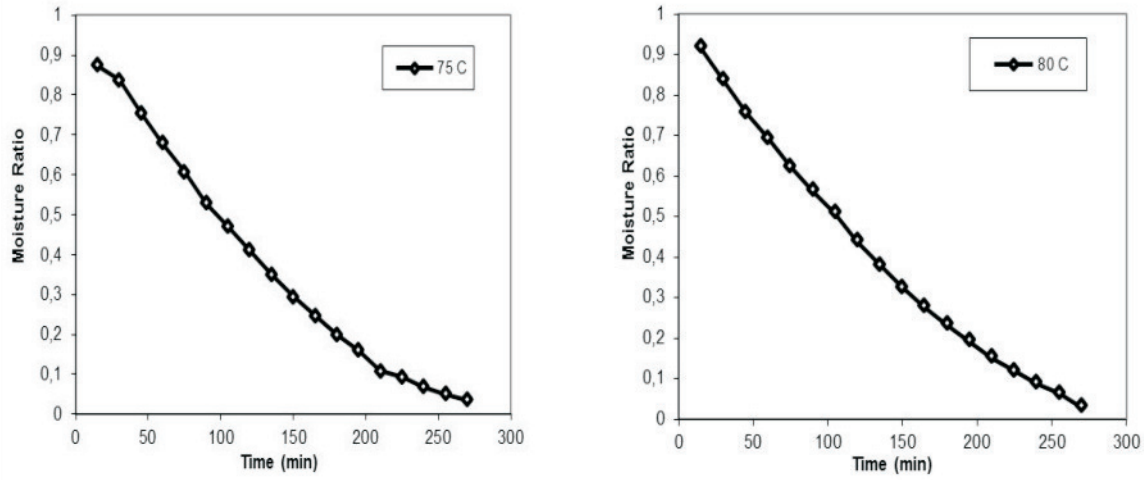

Figure 3. Variation of experimental moisture ratio of tomato slices with drying time at 75 and 80 °C.

For olive-waste cake, k and n changes between 0.00327 and 0.0181 and between 1.096 and 1.181 for Page's and Henderson & Pabis model at 50-90 °C for forest residues (33). For tomato drying, n and k values changes between 1.1985 and 1.2900 and between 0.003 and 0.006 for Page's model; between 1.0591 and 1.0755 and between 0.0018 and 0.0024 for Henderson & Pabis model at 55-70 °C (7).

Table 1. The estimated fitting parameters and constant values of mathematical models for drying kinetics of tomato slices at different temperatures.

Models	Temp.	Constants						Regression Coefficients		
	(°C)	a	b	c	d	k	n	R^2	SSE	RMSE
Page's	65	-	-	-	-	0.001403	1.372	0.9967	0.00447	0.01726
	70	-	-	-	-	0.00163	1.331	0.9924	0.01028	0.0253
	75	-	-	-	-	0.00146	1.333	0.9948	0.00705	0.021
	80	-	-	-	-	0.0015	1.328	0.993	0.00941	0.0242
Henderson & Pabis	65	1.141	-	-	-	-0.0097	-	0.980	0.0266	0.0421
	70	1.118	-	-	-	-0.00854	-	0.9793	0.02794	0.04179
	75	1.104	-	-	-	-0.00908	-	0.9739	0.0353	0.04701
	80	1.111	-	-	-	-0.00853	-	0.976	0.0313	0.0442
Logaritmic	65	-7.949	-	0.384	-	1.512	-	-0.155	1.335	0.3088
	70	-12.29	-	0.375	-	1.286	-	-0.133	1.355	0.3005
	75	-4.823	-	0.4021	-	1.322	-	-0.133	1.351	0.3001
	80	-4.824	-	0.3997	-	1.289	-	-0.133	1.343	0.2992
Wang & Sing	65	-0.006	$9.4e^{-6}$	-	-	-	-	0.9984	0.0022	0.0121
	70	-0.006	$8.9e^{-6}$	-	-	-	-	0.9982	0.0024	0.0122
	75	0.0055	$7.4e^{-6}$	-	-	-	-	0.9998	0.000268	0.004096
	80	0.0055	$7.3e^{-6}$	-	-	-	-	0.9997	0.00037	0.00486
Midilli	65	0.9696	-0.002	-	-	0.000139	1.343	0.9994	0.000786	0.000777
	70	0.9155	-0.001	-	-	0.000676	1.47	0.9984	0.000779	0.00746
	75	0.8979	-0.003	-	-	149.2	-6.51	0.976	0.0317	0.0476
	80	0.894	-0.003	-	-	2222	-26.39	0.9789	0.0283	0.0449
Polynomme	65	$1.46e^{-8}$	$4.9e^{-6}$	-0.006	1.012	-	-	0.9995	0.00067	0.00679
	70	$3.35e^{-8}$	$6.3e^{-6}$	-0.005	1.004	-	-	0.9999	0.000122	0.00295
	75	$2.39e^{-8}$	$-1.4e^{-6}$	-0.004	0.9627	-	-	0.9993	0.00101	0.00850
	80	$4.48e^{-9}$	$5.3e^{-6}$	-0.005	0.9920	-	-	0.9998	0.00032	0.00483

Model constants of c and d in polynommial model changed between -0.004 and -0.006 and between 0.9920 and 1.012 for the the tomato slices respectively. Based on the statistical test results (SSE, RMSE % and R^2), polynommial model gave better results compared to Page's, Henderson & Pabis, Wang & Sing, Weibull and Midilli equation. The R^2 values of the polynommial model for drying characteristics of tomato samples varied between 0.9993 and 0.9999 and had the lowest SSE and RMSE % values at 65-80 °C.

Effective Moisture Diffusivity (D_{eff}) and Activation Energy (E_a)

The moisture diffusivity (D_{eff}, m^2/ s) can be obtained from by plotting experimental drying data of the tomato powder Ln (M_R) versus time gives a straight line (32). The slope of the straight line of k is (equation 3):

$k= \pi^2 D_{eff} /4L^2$

where L is the half thickness of the sample in terms of meters. The thickness and diameters of samples was 4 mm and 80 mm respectively. The moisture diffusivity of tomato slices and regression coefficients of straight line were presented in Table 2. The diffusivity constant increased with increasing drying temperature and it varies between $5.86. 10^{-9}$ and $2.505. 10^{-8}$ m^2/ s for tomato samples. Moisture diffusivity constant varies between 8.10^{-10} and $2.17.10^{-9}$ m^2/s for grape marc and between $2.01.10^{-9}$ and $3.32.10^{-9}$ m^2/ s for grape pulp at the temperatures of 70-110 °C (11); between $0.702.10^{-9}$ and 3.32610^{-9} m^2/ s for coconut press cake at a temperatures of 65-75 °C (29), and between 5.65 and 7.53 10^{-10} m^2/ s for pre-treated tomato products at 55-70 °C (12). The diffusivity constant changes between 3.91 and 6.65 10^{-10} m^2/ s for untreated samples of tomato at a temperature of 55-70 °C (7) and between 4.89 10^{-10} and 9.9810^{-10} m^2/ s for the olive cake drying for the temperature range of 80-110 °C (12).

Table 2. Effective diffusivity values (Deff, m^2/ s) and regression constants of the straight lines for tomato slices.

Temperature (°C)	Regression constant	D_{eff} (m^2/ s)
65	0.9621	7.025 e^{-7}
70	0.9490	1.103e^{-6}
75	0.9583	2.01e^{-6}
80	0.9290	3.005e^{-6}

The temperature effect on the moisture diffusivity can be explained by equation (8) and activation energy was calculated by plotting the Ln D_{eff} versus the reciprocal of the drying temperature (1/T) in Figure 4.

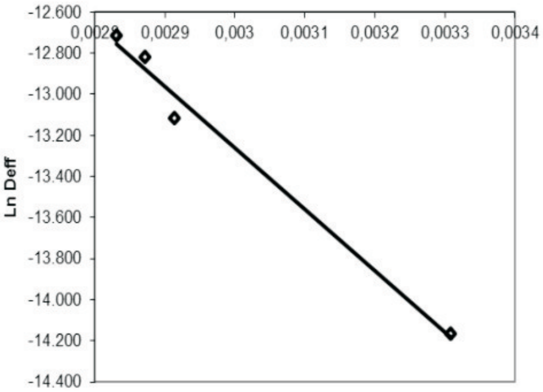

Figure 4. Temperature effect on the moisture diffusivity of tomato slices.

The activation energy value, Ea (kJ/ mole) was calculated as 24.94 kJ/mole for the tomato slices. The activation energy of the tomato sample was similiar to the pre-treated and untreated tomato products (17.40 kJ/ mole and 32.94 kJ/mole) respectively (7) but lower for red chili (41.95 kJ/mole) (33) and green peas drying (28.40 kJ/mole) (34).

CONCLUSION

Tomato slices were dried at different drying temperatures (65-80 °C) with convectional method at a final moisture content of 2-3 % (w.b). Experimental datas of the products were predicted Page's, Henderson & Pabis, Wang & Sing, Logaritmic, Midili, Weibull and Polynommial model. It can easily be seen that polynommial model gave better results than the other models and logaritmic model gave bad results within the models. Polynommial model can be used for describing the drying kinetics of the tomato slices. Effective moisture diffusivity values increased with increasing drying temperature which ranged from $5.86.10^{-9}$– $2.505.10^{-8}$ m2 /s for the tomato samples. It can be concluded that effective moisture diffusivity value increases with increasing temperature. The activation energy of the tomato slices was found as 24.94 kJ/mole.

REFERENCES

1. FAO 2005. FaoStat Database. http:// faostat. fao.org.

2. Guil-Guerrero JL, Rebolloso-Fuentes MM. 2009. Nutrient composition and antioxidant activity of eight tomato (*Lycopersicon esculentum*) varieties. *J Food Compos Anal*, 22, 123-129

3. Abjdayil B, Banat F, Jumah R, Al-Asheh S, Hammad SAC. 2004. Comparative study of rheological characteristics of tomato paste and tomato powder solutions. *Int J Food Prop*, 7 (3), 483-497.

4. Akanbi CT, Oludemi FO. 2004. Effect of processing and packaging on the lycopene content of tomato products. *Int J Food Prop*, 7 (1):139-152.

5. Cemeroglu B. 2004. Fruit and Vegetable Processing Thecnology. 2nd Edition. Food Technology Publishing, Ankara, 408- 409.

6. Masters K. 1985. Spray Drying Handbook. 4th Edition. John Wiley and Sons, New York.

7. Doymaz I. 2007. Air-drying characteristics of tomatoes. *J Food Eng*, 78, 1291-1297.

8. St. George SD, Cenkowski S, Muir WE. 2004. A rewiev of drying technologies for the preservation of nutritional compounds in waxy skinned fruit. North Central ASAE/CSAE Conference, Manitoba-Canada, 24-25.

9. Zanoni B, Peri C, Nani R, Lavelli V. 1999. Oxidative heat damage of tomato halves as affected by drying. *Food Res Int*, 31, 395-401.

10. Gaware TJ, Sutar N, Throat BN. 2010. Drying of tomato using different methods: comparison of dehydration and rehydration kinetics. *Drying Technol*, 28, 651-658.

11. Doymaz I, Akgun NA. 2009. Study of thin-layer drying of grape wastes. *Chem Eng Commun*, 196 (890), 890-900.

12. Doymaz I, Gorel O, Akgün NA. 2004. Drying characteristics of the solid by-product of olive oil extraction. *Biosystem Eng*, 88, 213-219.

13. Wang CY, Singh RP. 1978. A single layer drying equation for rough rice. ASAE paper n. 3001

14. Midilli A, Kucut H, Yapar Z. 2002. A new model for single layer drying. *Drying Technol*, 7, 1503-1513.

15. Vega-Galvez A, Miranda M, Diaz LP, Lopez L, Rodriguez K, Di Scala K. 2010. Effective moisture diffusivity determination and mathematical modelling of the drying curves of the olive-waste cake. *Bioresour Technol*, 101:7265-7270.

16. Yagcioglu A, Degirmencioglu A, Cagatay F. 1999. Drying characteristic of laurel leaves under different conditions. Proceeding of the 7th international congress on agricultural mechanization and energy. Faculty of Agriculture Cukurova University, Adana, 565-569.

17. Touil A, Chemkhi S, Zageouba F. 2010. Modelling of the drying kinetics of *Opuntia ficus indica* fruits and cladodes. *Int J Food Eng*, 6 (2): 1-15.

18. Phanpanich M, Mani S. 2009. Drying characteristics of pine forest residues. *Bioresour Technol*, 5(1): 108-121.

19. Chhninman MS. 1984. Evaluation of selected mathematical models for describing thin layer drying of in-shell pecans. Transactions of the ASAE, 27, 610-615.

20. Henderson SM, Pabis S. 1961. Grain drying theory. II. Temperature effects on drying coefficients. *J Agric Eng*, 6, 169-174.

21. Giovanelli G, Zanoni B, Lavelli V, Nani R. 2002. Water sorption, drying and antioxidan properties of dried tomato products. *J Food Eng*, 52, 135-141

22. Akanbi CT, Adeyemi RS, Ojo A. 2006. Drying characteristics and sorption isotherms of tomato slices. *J Food Eng*, 73, 141-146.

23. Akpinar EK, Bicer Y. 2004. Modelling of the drying of eggplants in thin layers. *Int J Food Sci Technol*, 39, 1-9.

24. Doymaz I. 2004. Effect of pre-treatments using potassium metabisulfide and alkaline etyl oleate on the drying kinetics of apricots. *Biosystems Eng*, 89, 281-287.

25. Kashaninejad M, Tabil LG. 2004. Drying characteristics of purslane. *Drying Technol*, 22, 2183-2200.

26. Akgün NA, Doymaz I. 2005. Modelling of olive cake thin-layer drying process. *J Food Eng*, 68, 455-461.

27. Akpinar EK, Bicer Y. 2007. Modelling of thin layer drying kinetics of sour cherry in solar dryer and under open sun. *J Sci Ind Res*, 66, 64-771.

28. Mok C, Hettiarachchy A. 1990. Moisture sorption characteristics of ground sunflower nutmeat and its products. *J Food Sci*, 3 (55), 786-789.

29. Jena S, Das H. 2007. Modelling for vacuum drying characteristics of coconut pres-cake. *J Food Eng*, 79, 92- 99.

30. Arifoglu U. 2005. Matlab 7.6. Applications of Simulink & Engineering. Publics of Alfa, İstanbul.

31. Gogus F, Maskan M. 2006. Air drying characteristics of solid waste of olive oil processing. *J Food Eng*, 72, 378-382.

32. Lomauro CJ, Bakshi AS, Labuza TP. 1985. Moisture transfer properties of dry and semimoist foods. *J Food Sci*, 50, 397-400.

33. Grupta P, Ahemd J, Shivhare US, Raghavan GSV. 2002. Drying characteristics of red chili. *Drying Technol*, 20, 1975-1987.

34. Simal S, Mulet A, Tarrazo J, Rosello C. 1996. Drying models for green peas. *Food Chem*, 55, 121-128.

35. Dadali G, Demirhan E, Ozbek E. 2007. Color change kinetics of spinach undergoing microwave drying. *Drying Technol*, 25, 1713-1723.