Mathematical Modeling to Study Drying Characteristic of Apple and Potato

Fateh Singh, V. K. Katiyar, and B. P. Singh

Abstract— Drying of fruits and vegetables is widely used phenomenon in food industries to produce them long time usable without affecting their quality and nutrition values. Water removal is the main factor of the reduction of mass and volume of food products during dehydration. Time and temperature have significant effects on the moisture removal during the drying process of foodstuffs. Mathematical modeling is a frequently used tool for the study of drying kinetics of fruits and vegetables. Therefore, in the present study our objective is to propose a mathematical model to study the drying characteristic of apple and potato during thin-layer drying. The validity of the proposed model is shown with the help of numerous experimental data taken from literature. A good fit of the proposed model to the experimental data is obtained. Further, the proposed model is compared to several existing thin-layer drying models.

Keywords— Apple and potato, Dehydration, Moisture Content, Temperature, Thin-Layer Drying.

I. Introduction

THE drying process of fruits and vegetables are often used in food industries to maintain the quality, nutrition values and extend the shelf-life of foods to make them long time usable. The use of drying of foodstuffs is very common to improve food stability and minimize chemical and physical changes during storage. Drying is the most extensively used technique for food preservation [1]-[5]. Fresh fruits and vegetables contain a large percentage of water. Drying of heat-sensitive materials of high moisture content requires exact knowledge of kinetics and reliable control of a drying process [1]. The aim of drying of food products is the removal of water to a certain level that can prevent the growth of mould and fungi and thus minimize microbial degradation [6]. There are various types of drying techniques that can be applied to reduce the water and hence attains the purpose of food preservation. Sun drying, microwave drying, microwave vacuum drying, hot air drying, osmotic dehydration, freeze drying, fluidized bed drying and spray-drying are broadly used techniques for drying of fruits and vegetables [6]. The above drying methods for different food products have been used by many researchers, for example, hot-air drying has been used for drying of apple [4], [5], [7], [8], potato [9]-[11], potato and carrot [12]; osmo-convective drying for apple [13]; thin layer solar drying for pumpkin, onion, green bean, stuff pepper, green pepper, [14], osmotic dehydration for apple [15]; freeze-drying for potato and apple [16]; fluidized bed drying for green beans, potatoes and peas [17], potato [18], [19] and microwave drying for potato [20].

Water removal from biological products (such as apple and potato) leads to reduced tension inside the cells which caused the amendment in cellular structure during drying [21]. As a result, it gives a considerable reduction in shape, size, mass and also, but not essentially, volume of food products. Therefore, dehydrated food products have many benefits such as convenience in use and minimize transportation, storage and packaging cost and time.

It is evident that the changes in the moisture content as a function of time characterize the drying behavior of agricultural materials [3]. In addition, there are several experimental studies available in literature that reported the thin layer drying behavior of several food products, for example, mulberries [22], red chilies [23], bananas [24], potato [21], [25], [26], , apples [27]-[29], potato, apple and pumpkin [30] by using hot air dryer. Drying of food products are greatly affected by the following factors: drying time, drying temperature, relative air humidity, air flow rate, surface area, volume and local or partial pressure [19].

The aim of the present work is to propose a mathematical model for calculating the variation of moisture content as a function of time during drying of apple and potato.

II. Mathematical Model

The thin-layer drying is defined by [30] as to dry one layer of sample or slices of fruit or vegetables. The drying phenomenon of these products can be described by the thin-layer drying models that can be categories as theoretical, semi-theoretical and empirical [31]. The first category of thin-layer drying model is considered for study the internal resistance to moisture transfer while other two categories are considered for study the external resistance to moisture transfer between air and product [32], [33]. The theoretical models are derived from Fick's second law of diffusion [31] while semi-theoretical models are generally derived from Fick's second law by its modifications and from Newton's

Fateh Singh is with the Department of Mathematics, Indian Institute of Technology Roorkee-247667 (UK), India. (corresponding author's phone: +911332286374; e-mail: fatehsinghsaini@gmail.com).

V. K. Katiyar is with the Department of Mathematics, Indian Institute of Technology Roorkee-247667, India.

B. P. Singh is with the Central Potato Research Institute, Shimla- 171001 (HP), India.

http://dx.doi.org/10.15242/IICBE.C914067

law of cooling [2].

In the present work we are more concern for semi-theoretical thin-layer drying model due to better prediction of results as compare to other models. The concept of thin-layer drying models for characterizing the drying behavior was suggested, initially, by Lewis [34], who derived the semi-theoretical model for porous hygroscopic materials, which is analogous with Newton's law of cooling. The following model was developed

$$MR = \frac{X - X_e}{X_0 - X_e} = \exp(-k\,t) \tag{1}$$

where MR is moisture ratio, k is drying constant (m^{-1}), t is drying time, X, X_e, X_0 are moisture content at any time, equilibrium and initial, respectively. Page [35] modified the Lewis model by adding a dimensionless empirical constant (n) and used it for study the drying behavior of shelled corns.

$$MR = \frac{X - X_e}{X_0 - X_e} = \exp(-k\,t^n) \tag{2}$$

For study the drying kinetics of soybeans, Overhults et al. [36] modified the Page model and obtained the following equation (this model is known as Modified Page-I Model)

$$MR = \frac{X - X_e}{X_0 - X_e} = \exp(-k\,t)^n \tag{3}$$

In addition, White et al. [37] make a little change in (3) to describe the drying kinetics of soybeans (this model is known as Modified Page-II Model)

$$MR = \frac{X - X_e}{X_0 - X_e} = \exp\left(-(k\,t)^n\right) \tag{4}$$

Further, for the drying of sweet potato, Diamante and Munro [38] modified the Page model and proposed the following equation (this model is known as Modified Page equation-II Model)

$$MR = \frac{X - X_e}{X_0 - X_e} = \exp\left(-k\left(t/l^2\right)^n\right) \tag{5}$$

where l is an empirical constant (dimensionless).

The drying process of apple and potato is considered as the external resistance to moisture transfer between air and product, therefore, the drying behavior of apple and potato can be characterized by semi-theoretical thin-layer drying models. The above discussed models have been tested for experimental data for apple and potato opted from literature. These models are inadequate to describe the drying behavior of apple and potato in last drying hours. Therefore, in this context we have proposed the following model by adding a linear term in the Lewis model for drying kinetics of apple and potato

$$MR = \frac{X - X_e}{X_0 - X_e} = \exp(-k\,t) - a\,k\,t \tag{6}$$

where k is the drying constant (m^{-1}) and a is the adjusting model constant (dimensionless) introduced for obtaining the best fit of the model to experimental data. The drying constant k depends on drying conditions, temperature, air velocity, humidity and drying methods. The moisture ratio MR can be calculated by (7) instead of $(X - X_e)/(X_0 - X_e)$ due to the small value of X_e as compare to X and X_0 [27].

$$MR = \frac{X}{X_0} \tag{7}$$

Therefore, (6) reduced to

$$MR = \frac{X}{X_0} = \exp(-k\,t) - a\,k\,t \tag{8}$$

III. Results and Discussion

The drying characteristics of apple and potato are presented in terms of moisture behavior as a function of time. In order to check the aptness of the proposed model, several experimental data of thin-layer drying of apple and potato have been used by extracted from literature. Values of parameters have been estimated by fitting the model to the experimental data. The nonlinear regression analysis was performed using the Origin software (OriginPro 8 SR0 v8.0724 (B724)). Although, the goodness of fit was assessed by using statistical test methods such as reduced chi-square (χ^2) and the root mean square error (RMSE), the coefficient of determination (R^2) were used as the primary criteria for suitability of the model. The lower RMSE and chi-square (χ^2) values and the higher R^2 values were chosen as the basis for goodness of fit.

The experimental data [8], [39] and [19] for apple and potato, respectively, have been extracted for moisture contents as a function of time for different temperature and air velocities. The extracted drying data of moisture content were converted to dimensionless moisture ratio (MR) using (7) and fitted to all the models discussed above. The graph between dimensionless moisture content and drying time at different drying temperature and air velocities are shown in Fig. 1 and Fig. 2 for apple while in Fig. 3 for potato. The drying model coefficients, statistical results and the comparison of the present model with existing models on the basis of R^2, RMSE and χ^2 are shown in the Table I and Table II for apple and

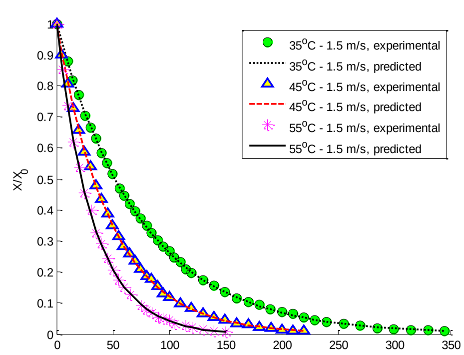

Fig. 1 Predicted and experimental [39] moisture ratio vs. drying time at different drying temperature and air velocity of apple.

http://dx.doi.org/10.15242/IICBE.C914067

TABLE I
STATISTICAL RESULTS AND VALUES OF CONSTANTS OF DIFFERENT MODELS FOR SEVERAL DRYING TEMPERATURE AND AIR VELOCITIES FOR APPLE

Model Name	Va (m/s)	T (°C)	Model Constants	χ^2	R^2 (COD)	RMSE (SD)	Ref
Lewis	1.5	35	k =0.01337	1.990e-5	0.9997	0.00446	[39]
$MR = \exp(-kt)$		45	k =0.02099	4.116e-5	0.9994	0.00642	
		55	k =0.03132	2.602e-5	0.9996	0.0051	
	3	60	k =0.01765	7.432e-4	0.9944	0.02726	[8]
		70	k =0.02378	8.449e-4	0.9930	0.02907	
		80	k =0.02769	9.632e-4	0.9933	0.03104	
Page	1.5	35	k =0.01410, n =0.98796	1.686e-5	0.9997	0.00411	[39]
$MR = \exp(-kt^n)$		45	k =0.02198, n =0.9885	3.946e-5	0.9995	0.00628	
		55	k =0.03030, n =1.000899	2.516e-5	0.9997	0.00502	
	3	60	k =0.01007, n =1.1397	2.128e-4	0.9985	0.01459	[8]
		70	k =0.01371, n =1.14956	2.203e-4	0.9983	0.01484	
		80	k =0.01539, n =1.16752	1.933e-4	0.9987	0.01391	
Modified Page-I	1.5	35	k =0.01267, n =1.05571	2.039e-5	0.9997	0.00452	[39]
$MR = \exp(-kt)^n$		45	k =0.01587, n =1.3225	4.248e-5	0.9994	0.00652	
		55	k =0.01939, n =1.61543	2.710e-5	0.9996	0.00521	
	3	60	k =0.01455, n =1.21288	8.175e-4	0.9944	0.02859	[8]
		70	k =0.01689, n =1.40787	9.099e-4	0.9930	0.03017	
		80	k =0.01823, n =1.51902	0.00106	0.9933	0.03255	
Modified Page-II	1.5	35	k =0.01339, n =0.98819	1.685e-5	0.9998	0.00411	[39]
$MR = \exp\left(-(kt)^n\right)$		45	k =0.02102, n =0.98877	3.946e-5	0.9995	0.00628	
		55	k =0.03126, n =1.00915	2.516e-5	0.9997	0.00502	
	3	60	k =0.01769, n =1.14258	2.126e-4	0.9985	0.01458	[8]
		70	k =0.02397, n =1.15133	2.202e-4	0.9983	0.01484	
		80	k =0.02802, n =1.1683	1.933e-4	0.9987	0.0139	
Modified Page equation-II	1.5	35	k =0.00873, n =0.98784, l =0.78433	1.728e-5	0.9997	0.00416	[39]
$MR = \exp\left(-k\left(t/l^2\right)^n\right)$		45	k =0.01045, n =0.98824, l =0.68615	4.079e-5	0.9995	0.00639	
		55	k =0.01851, n =1.00875, l =0.78294	2.626e-5	0.9997	0.00512	
	3	60	k = 0.00684, n =1.13882, l =0.84294	2.366e-4	0.9985	0.01538	[8]
		70	k =0.00750, n =1.14801, l =0.76671	2.389e-4	0.9983	0.01546	
		80	k =0.00723, n =1.16591, l =0.7216	2.149e-4	0.9987	0.01466	
Present work	1.5	35	k =0.01336, a =-1.029e-4	1.095e-5	0.9999	0.00331	[39]
$MR = \exp(-kt) - akt$		45	k =0.02104, a =-2.139e-4	1.776e-5	0.9998	0.00421	
		55	k =0.03115, a =6.748e-4	2.047e-5	0.9998	0.00452	
	3	60	k =0.01546, a =0.0389	9.312e-5	0.9994	0.00965	[8]
		70	k =0.02112, a =0.03452	1.146e-4	0.9991	0.01071	
		80	k =0.02561, a =0.02055	1.714e-4	0.9989	0.01309	

Va = Air velocity, T = Temperature, k = drying constant (m^{-1}), χ^2 = Chai square, R^2 = Coefficient of determination, RMSE = Root Mean Square Error, Ref = References of experimental data used for statistical results.

potato, respectively. In all cases, the value of R^2 lies between 0.9930 to 0.9999 for apple and 0.9989 to 0.9999 for potato while the values of RMSE lies between 0.00331 to 0.03255 for apple, 0.00351 to 0.01239 for potato and the values of χ^2 lies between 1.1E-05 to 0.00106 for apple and 1.23E-05 to 0.0001534 for potato. The statistical results showed that all the models, presented in this study, are fitted well to the experimental data. But the model developed in present work is better due to the lowest value of RMSE and χ^2 and the highest value of R^2 among all the corresponding values in each case.

Fig. 1 depicts that the present model has been fitted very well to experimental data which was carried out by [39] at the drying temperature 35°C, 45°C and 55°C and air velocity 1.5 m/s for apple. Fig. 2 depicts the fitted curve of the present model for the experimental data [8] at drying temperature 60°C, 70°C and 80°C and air velocity 3 m/s for apple. The statistical results are shown in Table I. As can be expected that, at lower drying temperature drying process goes slow and take the long time for the completion and reached at a constant drying rate (Fig. 1).

In the initial hour of drying, the rate of moisture removal is high and it becomes slower after a certain level of moisture content. Whereas for the high drying temperature and air velocity, the rate of water removal is high as compare to the low drying temperature and air velocity (Fig. 2). Further, the time to complete drying process is also less.

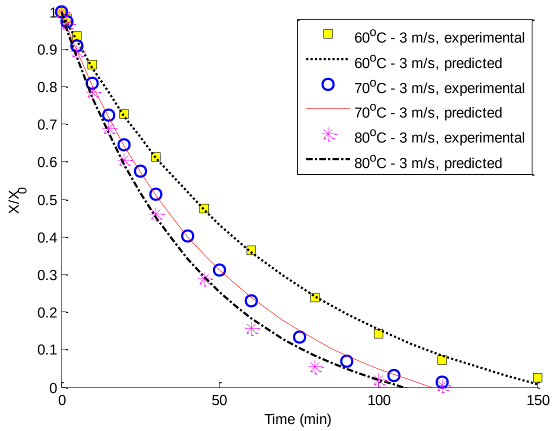

Fig. 2 Predicted and experimental [8] moisture ratio vs. drying time at different drying temperature and air velocity of apple.

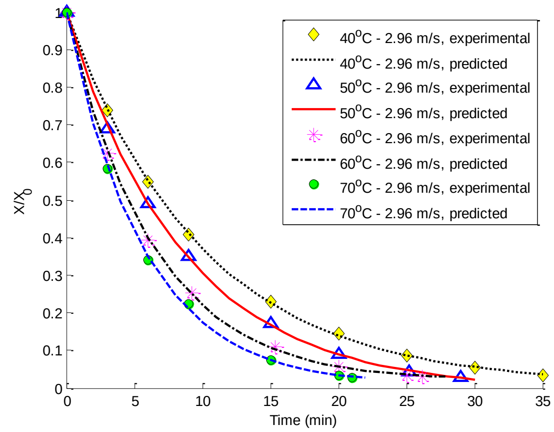

Fig. 3 Predicted and experimental [19] moisture ratio vs. drying time at different drying temperature and air velocity of potato.

Fig. 3 presented the experimental data of [19] for potato drying at temperature 40°C, 50°C, 60°C, 70°C and air velocity 2.96 m/s; and the fitted curve of our model to the data. The statistical results are shown in Table II. It is clear from the Fig. 3 that during drying, water from the potato removes in exponential fashion as drying time increases. Further, high temperature and air velocity increases the drying rate. It is also noticed that the water removal rate in potato is high as compare to apple. It can be seen from all the figures and above discussion that the drying temperature and air velocity has a

TABLE II
STATISTICAL RESULTS AND VALUES OF CONSTANTS OF DIFFERENT MODELS FOR SEVERAL DRYING TEMPERATURE AND AIR VELOCITIES FOR POTATO

Model Name	Va (m/s)	T (°C)	Model Constants	χ^2	R^2 (COD)	RMSE (SD)	Ref
Lewis $MR = \exp(-kt)$	2.96	40	k =0.09872	4.306e-5	0.9996	0.00656	[19]
		50	k =0.11928	3.755e-5	0.9996	0.00613	
		60	k =0.15085	9.146e-5	0.9992	0.00956	
		70	k =0.17455	8.180e-5	0.9993	0.00904	
Page $MR = \exp(-kt^n)$	2.96	40	k =0.09644, n =1.00989	4.682e-5	0.9997	0.00684	[19]
		50	k =0.12072, n =0.99459	4.298e-5	0.9997	0.00656	
		60	k =0.17312, n =0.93512	4.237e-5	0.9997	0.00651	
		70	k =0.18775, n =0.96134	5.963e-5	0.9996	0.00772	
Modified Page-I $MR = \exp(-kt)^n$	2.96	40	k =0.03442, n =2.86818	5.023e-5	0.9996	0.00709	[19]
		50	k =0.03783, n =3.15274	4.381e-5	0.9997	0.00662	
		60	k =0.04273, n =3.56071	1.534e-4	0.9989	0.01239	
		70	k =0.04404, n =3.96351	9.816e-5	0.9993	0.00991	
Modified Page-II $MR = \exp\left(-(kt)^n\right)$	2.96	40	k =0.09867, n =1.00969	4.682e-5	0.9997	0.00684	[19]
		50	k =0.11933, n =0.99488	4.298e-5	0.9997	0.00656	
		60	k =0.15329, n =0.93493	4.237e-5	0.9997	0.00651	
		70	k =0.17554, n =0.96131	5.963e-5	0.9996	0.00772	
Modified Page equation-II $MR = \exp\left(-k\left(t/l^2\right)^n\right)$	2.96	40	k =4.21277, n =0.05198, l =7.90316	5.619e-5	0.9996	0.0075	[19]
		50	k =0.00580, n =0.99299, l =0.21649	5.172e-5	0.9997	0.00719	
		60	k =0.00968, n =0.93610, l =0.21451	5.090e-5	0.9997	0.00713	
		70	k =0.01854, n =0.96086, l =0.29966	7.455e-5	0.9996	0.00863	
Present work $MR = \exp(-kt) - akt$	2.96	40	k =0.09993, a =-0.00206	1.233e-5	0.9999	0.00351	[19]
		50	k =0.11820, a =0.00172	3.531e-5	0.9998	0.00594	
		60	k =0.15435, a =-0.0037	2.948e-5	0.9998	0.00543	
		70	k =0.17769, a =-0.00161	3.157e-5	0.9998	0.00562	

Va = Air velocity, T = Temperature, k = drying constant (m^{-1}), χ^2 = Chai square, R^2 = Coefficient of determination, RMSE = Root Mean Square Error, Ref = References of experimental data used for statistical results.

significant effect on drying time. As the drying temperature or air velocity increases drying time decreases.

It is evident from the experimental studies that during drying of apple and potato, cells (or tissues) in these products shrinks and internal tension on the cell wall are developed due to water removal. As a result internal structure undergoes deformation. The deformation and mechanical properties such as tension-stretch ratio [40] and turgor pressure-stretch ratio [41] of soft tissues of apple and potato was studied. To study these mechanical properties of apple and potato a strain energy function was used.

IV. Conclusion

In the present study, a mathematical model is proposed to study drying characteristic of apple and potato. The model is validated with the help of several experimental data extracted from literature. Further, the proposed model is compared with several already developed drying models for different food products on the basis of RMSE, reduced chi-square and coefficient of determination. The results showed that the model proposed in present work is better as compare to existing models. The present model may be helpful for food industries to analyze drying kinetics of apple and potato so that the quality of these products can be maintained.

Acknowledgment

Fateh Singh is grateful to the Council of Scientific and Industrial Research (CSIR) Delhi, India for providing financial support during the preparation of this work.

References

[1] S. Chemkhi, F. Zagrouba, and A. Bellagi, "Mathematical model for drying of highly shrinkable media," *Drying Technology,* vol. 22, pp. 1023-1039, 2004.
http://dx.doi.org/10.1081/DRT-120038578

[2] Z. Erbay and F. Icier, "A review of thin layer drying of foods: Theory, modeling, and experimental results," *Critical Reviews in Food Science and Nutrition,* vol. 50, pp. 441-464, May 2010.
http://dx.doi.org/10.1080/10408390802437063

[3] A. Ghazanfari, S. Emami, L. G. Tabil, and S. Panigrahi, "Thin-layer drying of flax fiber: II. Modeling drying process using semi-theoretical and empirical models," *Drying Technology,* vol. 24, pp. 1637-1642, 2006.
http://dx.doi.org/10.1080/07373930601031463

[4] K. Rayaguru and W. Routray, "Mathematical modeling of thin layer drying kinetics of stone apple slices," *International Food Research Journal,* vol. 19, pp. 1503-1510, 2012 .

[5] D. Velić, M. Planinić, S. Tomas, and M. Bilić, "Influence of airflow velocity on kinetics of convection apple drying," *Journal of Food Engineering,* vol. 64, pp. 97-102, 2004.
http://dx.doi.org/10.1016/j.jfoodeng.2003.09.016

[6] S. V. Jangam, C. L. Law, and A. S. Mujumdar, *Drying of Foods, Vegetables and Fruits* vol. 2. Singapore, 2011.

[7] J. Wang and Y. Chao, "Drying characteristics of irradiated apple slices," *Journal of Food Engineering,* vol. 52, pp. 83-88, Mar 2002.
http://dx.doi.org/10.1016/S0260-8774(01)00090-5

[8] E. L. Schultz, M. M. Mazzuco, R. A. F. Machado, A. Bolzan, M. B. Quadri, and M. G. N. Quadri, "Effect of pre-treatments on drying, density and shrinkage of apple slices," *Journal of Food Engineering,* vol. 78, pp. 1103-1110, Feb 2007.
http://dx.doi.org/10.1016/j.jfoodeng.2005.12.024

[9] L. Hassini, K. Smida, S. Azzouz, and A. Belghith, "Experimental study of drying behaviour of an agricultural product," in *Proceedings of the 13th International Drying Symposium*, Beijing, China, 27-30, 2002, pp. 1457-1463.

[10] E. Akpinar, A. Midilli, and Y. Bicer, "Single layer drying behaviour of potato slices in a convective cyclone dryer and mathematical modeling," *Energy Conversion and Management,* vol. 44, pp. 1689-1705, 2003.
http://dx.doi.org/10.1016/S0196-8904(02)00171-1

[11] L. Hassini, S. Azzouz, R. Peczalski, and A. Belghith, "Estimation of potato moisture diffusivity from convective drying kinetics with correction for shrinkage," *Journal of Food Engineering,* vol. 79, pp. 47-56, Mar 2007.
http://dx.doi.org/10.1016/j.jfoodeng.2006.01.025

[12] J. Srikiatden and J. S. Roberts, "Predicting moisture profiles in potato and carrot during convective hot air drying using isothermally measured effective diffusivity," *Journal of Food Engineering,* vol. 84, pp. 516-525, Feb 2008.
http://dx.doi.org/10.1016/j.jfoodeng.2007.06.009

[13] H. S. Ramaswamy and N. H. van Nieuwenhuijzen, "Evaluation and modeling of two-stage osmo-convective drying of apple slices," *Drying Technology,* vol. 20, pp. 651-667, 2002.
http://dx.doi.org/10.1081/DRT-120002822

[14] O. Yaldýz and C. Ertekýn, "Thin layer solar drying of some vegetables," *Drying Technology: An International Journal,* vol. 19, pp. 583-597, 2001.
http://dx.doi.org/10.1081/DRT-100103936

[15] B. A. Souraki, M. Ghavami, and H. Tondro, "Correction of moisture and sucrose effective diffusivities for shrinkage during osmotic dehydration of apple in sucrose solution," *Food and Bioproducts Processing,* vol. 92, pp. 1-8, 2014.
http://dx.doi.org/10.1016/j.fbp.2013.07.002

[16] S. Khalloufi, J. L. Robert, and C. Ratti, "Solid foods freeze-drying simulation and experimental data," *Journal of Food Process Engineering,* vol. 28, pp. 107-132, Apr 2005.
http://dx.doi.org/10.1111/j.1745-4530.2005.00379.x

[17] W. Senadeera, B. R. Bhandari, G. Young, and B. Wijesinghe, "Influence of shapes of selected vegetable materials on drying kinetics during fluidized bed drying," *Journal of Food Engineering,* vol. 58, pp. 277-283, Jul 2003.
http://dx.doi.org/10.1016/S0260-8774(02)00386-2

[18] S. B. Bakal, G. P. Sharma, S. P. Sonawane, and R. C. Verma, "Kinetics of potato drying using fluidized bed dryer," *Journal of food science and technology,* vol. 49, pp. 608-613, Oct 2012.

[19] R. A. Chayjan, "Modeling some drying characteristics of high moisture potato slices in fixed, semi fluidized and fluidized bed conditions," *Journal of Agricultural Science and Technology,* vol. 14, pp. 1229-1241, Nov 2012.

[20] H. Darvishi, A. R. Asl, A. Asghari, G. Najafi, and H. A. Gazori, "Mathematical modeling, moisture diffusion, energy consumption and efficiency of thin layer drying of potato slices," *Journal of Food Processing & Technology,* vol. 04, 2013.

[21] M. Shekofteh, F. E. Cherati, S. Kamyab, and Y. Hosseinpor, "Study of Shrinkage of Potato Sheets during Drying in Thin-Layer Dryer," *Research Journal of Applied Sciences, Engineering and Technology,* vol. 4, pp. 2677-2681, 2012.

[22] I. Doymaz, "Drying kinetics of white mulberry," *Journal of Food Engineering,* vol. 61, pp. 341-346, Feb 2004.
http://dx.doi.org/10.1016/S0260-8774(03)00138-9

[23] P. Gupta, J. Ahmed, U. S. Shivhare, and G. S. V. Raghavan, "Drying characteristics of red chilli," *Drying Technology,* vol. 20, pp. 1975-1987, 2002.
http://dx.doi.org/10.1081/DRT-120015579

[24] W. P. da Silva, C. M. D. P. S. e Silva, F. J. A. Gama, and J. P. Gomes, "Mathematical models to describe thin-layer drying and to determine drying rate of whole bananas," *Journal of the Saudi Society of Agricultural Sciences,* vol. 13, pp. 67-74, 2014.
http://dx.doi.org/10.1016/j.jssas.2013.01.003

[25] H. Iyota, N. Nishimura, T. Onuma, and T. Nomura, "Drying of sliced raw potatoes in superheated steam and hot air," *Drying Technology,* vol. 19, pp. 1411-1424, 2001.
http://dx.doi.org/10.1081/DRT-100105297

[26] A. Yadollahinia and M. Jahangiri, "Shrinkage of potato slice during drying," *Journal of Food Engineering,* vol. 94, pp. 52-58, 2009.
http://dx.doi.org/10.1016/j.jfoodeng.2009.02.028

[27] K. Sacilik and A. K. Elicin, "The thin layer drying characteristics of organic apple slices," *Journal of Food Engineering,* vol. 73, pp. 281-289, Apr 2006.
http://dx.doi.org/10.1016/j.jfoodeng.2005.03.024

[28] Z. F. Wang, J. H. Sun, F. Chen, X. J. Liao, and X. S. Hu, "Mathematical modelling on thin layer microwave drying of apple pomace with and without hot air pre-drying," *Journal of Food Engineering*, vol. 80, pp. 536-544, May 2007. http://dx.doi.org/10.1016/j.jfoodeng.2006.06.019

[29] E. Meisami-asl and S. Rafiee, "Mathematical modeling of kinetics of thin-layer drying of apple (var. Golab)," *Agricultural Engineering International: CIGR Journal*, , vol. XI, 2009.

[30] E. K. Akpinar, "Determination of suitable thin layer drying curve model for some vegetables and fruits," *Journal of Food Engineering*, vol. 73, pp. 75-84, Mar 2006. http://dx.doi.org/10.1016/j.jfoodeng.2005.01.007

[31] P. C. Panchariya, D. Popovic, and A. L. Sharma, "Thin-layer modelling of black tea drying process," *Journal of Food Engineering*, vol. 52, pp. 349-357, May 2002. http://dx.doi.org/10.1016/S0260-8774(01)00126-1

[32] S. M. Henderson, "Progress in developing the thin layer drying equation," *Transactions of ASAE*, vol. 17, pp. 1167–1172, 1974. http://dx.doi.org/10.13031/2013.37052

[33] T. Whitaker, H. J. Barre, and M. Y. Hamdy, "Theoretical and experimental studies of diffusion in spherical bodies with a variable diffusion coefficients," *Transactions of ASAE*, vol. 11, pp. 668–672, 1969. http://dx.doi.org/10.13031/2013.38924

[34] W. K. Lewis, "The Rate of Drying of Solid Materials," *Journal of Industrial & Engineering Chemistry*, vol. 13, pp. 427-432, May 1921. http://dx.doi.org/10.1021/ie50137a021

[35] G. E. Page, "Factors influencing the maximum rate of air drying shelled corn in thin-layers," M.S.Thesis, Purdue University, West Lafayette, Indiana, 1949.

[36] D. G. Overhult, G. M. White, H. E. Hamilton, and I. J. Ross, "Drying soybeans with heated air," *Transactions of the ASAE*, vol. 16, pp. 112-113, 1973. http://dx.doi.org/10.13031/2013.37459

[37] G. M. White, T. C. Bridges, O. J. Loewer, and I. J. Ross, " Seed coat damage in thin layer drying of soybeans as affected by drying conditions," *ASAE paper no. 3052*, 1978.

[38] L. M. Diamante and P. A. Munro, "Mathematical modelling of the thin layer solar drying of sweet potato slices," *Solar Energy*, vol. 51, pp. 271–276, 1993. http://dx.doi.org/10.1016/0038-092X(93)90122-5

[39] I. Zlatanović, M. Komatina, and D. Antonijević, "Low-temperature convective drying of apple cubes," *Applied Thermal Engineering*, vol. 53, pp. 114-123, 2013. http://dx.doi.org/10.1016/j.applthermaleng.2013.01.012

[40] F. Singh, V. K. Katiyar, and B. P. Singh, "A new strain energy function to characterize apple and potato tissues," *Journal of Food Engineering*, vol. 118, pp. 178-187, Sep 2013. http://dx.doi.org/10.1016/j.jfoodeng.2013.04.006

[41] F. Singh, V. K. Katiyar, and B. P. Singh, "Analytical study of turgor pressure in apple and potato tissues," *Postharvest Biology and Technology*, vol. 89, pp. 44-48, Mar 2014. http://dx.doi.org/10.1016/j.postharvbio.2013.11.007