Thin layer drying kinetics of taro root (*Colocasia esculenta* L.)

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Abstract: Appropriate drying model is an important attribute for describing the drying kinetics of food products. Thin layer drying of taro roots were performed in a laboratory scale hot air dryer operated at 50°C, 60°C and 70°C temperature with air velocity of 0.5 ms^{-1}. Analysis of the result exhibits that drying of taro roots took place in falling rate period. Thin layer model such as Henderson-Pabis, Page and Lewis equation were studied to fit with the experimental data using nonlinear regression analysis. The suitable drying model was selected based on chi square (χ^2), root mean square error and relative percent error. Study of goodness of fit indicated that among the proposed models, Page equation gave better fit than all drying conditions used. Effective moisture diffusivity was determined through simplified Fick's second law of diffusion. Activation energy for moisture removal was described by Arrhenius equation and found as 18.01$kjmol^{-1}$.

Keywords: drying kinetics, taro roots, thin layer drying, effective moisture diffusivity, activation energy

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1 Introduction

Drying, the oldest method for the processing and preservation of freshly harvested agricultural produce has long been practiced by the human and quality of the finished product greatly depends on it. The purpose of drying is to reduce the moisture content in a certain level to prevent the microbial deterioration and most of the chemical reactions within the food components (Mondal et al., 2019). The storage and packaging of dried products takes lower spaces as it losses volume and weight through the drying process as well as makes the transportation system easier (Mujumdar, 1995). Traditionally, natural sun drying is widely practiced for the drying of agricultural produce throughout the world which contaminates dust, foreign particle and insects with the dried products. Therefore, drying of these product should be accomplished in a controlled environment which retains the product quality.

Taro is an important root crop of superior food value which is comprehensively cultivated in the many countries of the sub-tropical and tropical region of the world (Jane et al., 1992). The consumption of taro and its product as a root and tuber crop with the incorporation of another food is increasing day by day (Wang, 1983). Demand of taro and taro-based products are swelling at present age and commonly found in the most of the super market as first food. In addition to this, it offers great nutritional values like carbohydrate, mucilage and 70-80% minute starch granule which is readily digested by human (Kaushal et al., 2012). It is also an excellent source of minerals (calcium, phosphorous, and iron), high in fiber, vitamin C and vitamin B complex like thiamine, riboflavin and niacin which has a significant effect on human diet (Kaushal and Sharma, 2013). Apart from these uses, taro is also used as a biodegradable material in the plastic industry (Darkwa and Darkwa, 2013).

Freshly harvested tuber crops are highly perishable as it possesses high moisture content up-to 83% on wet basis

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(wb) depending on different variety (FAO, 1999). Unprocessed taro roots have a shelf life of at best 15-20 days (Lebot, 2009). One-third of the total production of taro corm is lost after harvesting due to the inapt processing technique, microbial deterioration, and as they freely respired (Agbor-Egbe, 1991). Various processing methods have been documented for the further use of taro-based products by several researchers such as stored at a room temperature in a humid area (Lebot, 2009), treatment with selected chemicals before store in aplastic bag (Baidoo et al., 2014), freeze drying of the taro roots (Njintang, 2003), solar drying (Whitfield, 2000).

Drying is usually defined as a complex method in which continuous weight loss of products take place due to the simultaneous heat and moisture transfer. Therefore, control of drying parameters under different drying technique of this complex method is an important subject through the engineering facts (Mondal et al., 2019). Numerous mathematical methods are readily accessible to define the drying process of which thin layer drying are typically used along with describing the drying behavior of agricultural produce. Numerous research studies have been performed to know the drying characteristics of different food products by several researchers. For example, eggplant (Ertekin and Yaldiz, 2004), tomato (Agarry, 2016), pumkin (Onwude et al., 2016), red chilli (Kamalakar et al., 2014), okra (Afolabi, 2014; Doymaz, 2005), carrot (Darvishi et al., 2012; Prabhanjan et al., 1995), grape (Pangavhane et al., 1999), grape seed (Roberts et al., 2008), banana (Dandamrongrak et al., 2002), plum (Sabarez et al., 1997), green pepper, stuffed pepper, green bean and onion (Yaldiz, and Ertekin, 2001), rough rice (Basunia and Abe, 2001), mushroom and pollen (Midilli et al., 1999).

The objective of this study is to investigate the hot air-drying kinetics of taro root which have not been reported up to date. A through thin layer modeling analysis tactics was also aimed to present which may readily be used to describe the drying kinetics of taro root through appropriate drying model.

2 Theoretical aspect

2.1 Mathematical modeling of hot air-drying curves

Thin layer drying models are widely used to describe the drying phenomenon of food materials in a unified way regardless of the controlling mechanism (Kingsly et al., 2007). Unaccomplished moisture ratio during drying in case thin layer drying is expressed by the Equation 1.

$$\mathrm{MR}=\frac{\mathrm{M}-\mathrm{M_e}}{\mathrm{M_o}-\mathrm{M_e}} \tag{1}$$

Where, MR is the dimensionless partial moisture ratio, M the average moisture content at time t, M_o and M_e the initial moisture content and equilibrium moisture content respectively, on dry weight basis.

The drying kinetics of various food materials are quantified through the simplified drying models (Bruce, 1985; Parti, 1993; Sogi et al., 2003). Thin layer drying models that are mostly used to describe the drying behavior of food materials are the Henderson-Pabis model:

$$\mathrm{MR}=\frac{\mathrm{M}-\mathrm{M_e}}{\mathrm{M_o}-\mathrm{M_e}}=\mathrm{a}\exp(-\mathrm{kt}) \tag{2}$$

The Page model:

$$\mathrm{MR}=\frac{\mathrm{M}-\mathrm{M_e}}{\mathrm{M_o}-\mathrm{M_e}}=\exp(-\mathrm{kt^n}) \tag{3}$$

and the Lewis model:

$$\mathrm{MR}=\frac{\mathrm{M}-\mathrm{M_e}}{\mathrm{M_o}-\mathrm{M_e}}=\exp(-\mathrm{kt}) \tag{4}$$

Where k is the drying rate constant, n and a are the empirical constant in the respective model. Based on the coefficient of determination (R^2) the constant in the model were determined from the developed drying curve at different drying temperature.

The simplified form of the Henderson-Pabis model is

$$\ln(\mathrm{MR})=-\mathrm{kt}+\ln(\mathrm{a}) \tag{5}$$

The parameters of equations were determined by non-linear regression analysis using the software OriginLab (version 16)

2.2 Estimation of effective moisture diffusivity and activation energy

Mechanism of moisture transfer within food material can be characterized with effective moisture diffusivity. Effective moisture diffusivity is anticipated to be only physical mechanism for the transfer of water from core to material surface during the drying process. Effective moisture diffusivity can be defined according to a mathematical model mostly known as Fick’s second law of diffusion which relates the relationship between moisture ratio and effective moisture diffusivity. Mathematical evaluation of the Fick's second law of diffusion is expressed by the Equation 6.

$$\frac{\partial \mathrm{m}}{\partial \mathrm{t}} = \mathrm{D_{eff}}\left[\frac{\partial^2 \mathrm{m}}{\partial \mathrm{r}^2} + \frac{2}{\mathrm{r}}\frac{\partial \mathrm{m}}{\partial \mathrm{r}}\right] \tag{6}$$

Fick's second law of diffusion is largely studied for the solution of thin layer drying of various foods. The analytical solution for the diffusion equation for flat food material is given as the following equation (Crank, 1975):

$$\mathrm{MR} = \frac{\mathrm{M}-\mathrm{M_e}}{\mathrm{M_0}-\mathrm{M_e}} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2\mathrm{D_{eff}}t}{4r^2}\right) \tag{7}$$

Equation 9 assumes that uniform distribution of initial moisture, negligible temperature gradient, negligible volume shrinkage during drying and negligible external resistant (Ochooa-Martinez and Ayala-Aponte, 2009). Reviews on extended drying period (n=1) stated that simplified form of the Equation 7 is a linear logarithmic equation as expressed in Equation 8 (Pala et al., 1996; Nuh and Brinkworth, 1997; Feng, 2000; Agarry et al., 2013):

$$\ln(\mathrm{MR}) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2\mathrm{D_{eff}}}{4r^2}t\right) \tag{8}$$

The effective moisture diffusivity is determined from the plot of the natural logarithm of moisture ratio (ln(MR)) versus time (t) using the following equation:

$$\mathrm{D_{eff}} = \frac{\mathrm{Slope}(r^2)}{4\pi^2} \tag{9}$$

Figure 6 shows the Arrhenius type relationship between effective moisture diffusivity and the reciprocal of absolute temperature and expressed by the following equation:

$$\mathrm{D_{eff}} = \mathrm{D_0}\exp\left(-\frac{\mathrm{E_a}}{\mathrm{R(T+273.15)}}\right) \tag{10}$$

Where D_0 is the pre-exponential factor of Arrhenious equation ($m^2\ s^{-1}$), E_a is the activation energy ($kJ\ mol^{-1}$), T is the absolute temperature of air (°C) and R is the molar gas constant ($kJ\ molK^{-1}$). The activation energy was calculated from the slope of the straight line in Figure 5.

3 Materials and methods

3.1 Sample preparation

The taro roots of bilashi variety were used to conduct the experiment. The pictures of the experimental taro root are shown in Figure 1. The samples were cleaned manually and washed with fresh water. The taro roots were peeled and cut into 4.0 mm thickness through a sharp and sterilize knife. Drying experiment was carried out in Food Process Engineering Laboratory, Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur. The time of conducting experiment was September, 2019.

Figure 1 Experimental taro root

3.2 The laboratory scale hot air cabinet dryer

A laboratory scale cabinet dryer (Shanghai Experimental Apparatus Company Limited, 101C-3B, China) with operating features of 220 V and 50 Hz were used to accomplish the drying experiments (Figure 2). The dryer was capable to work at various temperature levels and had a digital control facility to maintain the processing time. Drying air velocity during experiment was $1.03\pm0.1\ m\ s^{-1}$.

Figure 2 Experimental cabinet dryer

3.3 Hot air-drying experiments

In order to carry out the drying experiments, 10 g of sliced taro sample was weighed using digital balance (Electronic balance AS-80) with a measurement precision of 0.001 g. The samples were then placed on the tray in single layer inside of the dryer. The samples were dried at 50°C, 60°C and 70°C, respectively. Moisture content of the samples was recorded regularly of every 30 min. The drying process was continued until it reached to constant weight in two subsequent intervals. Initial moisture content of fresh sample and final moisture content of dried samples were determined for each drying experiment at 105°C for 20 hours.

3.4 Assessment of goodness of fit

The non-linear regression analysis was performed using the OriginLab computer program. The goodness of fit for each model was evaluated based on the chi square (χ^2), root mean square error (RMSE), and relative percent error (PE). The experimental moisture ratio was compared with the predicted moisture ratio using the chi square, root mean square error and relative percent error as expressed by the following equations (McMinn, 2006).

$$\chi 2 = \frac{1}{\mathrm{N-n}} \sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{MR_{exp,i}} - \mathrm{MR_{predict,i}})^2 \qquad (11)$$

$$\mathrm{RMSE} = [\frac{1}{\mathrm{n}} \sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{MR_{exp,i}} - \mathrm{MR_{predict,i}})]^2 \qquad (12)$$

$$\mathrm{PE}\ (\%) = \frac{100}{\mathrm{n}} \sum_{\mathrm{i=1}}^{\mathrm{n}} \frac{|\mathrm{M_{exp,i}} - \mathrm{M_{predict,i}}|}{\mathrm{M_{exp,i}}} \qquad (13)$$

Where $\mathrm{MR_{exp,i}}$ $\mathrm{MR_{predict,i}}$ is the experimental and predicted moisture ratio, respectively, N is the number of observations, and n is the number of constant. The lower the values of χ^2 and RMSE as approaches to zero, indicates the better fitness of the experiment with the predicted model (Ertekin and Yaldiz, 2004). Relative percentage error compares the absolute difference between experimental moisture content predicted moisture content in dry basis. The values of PE less than 10% indicate better fit with the predicted model (McLaughlin and Magee, 1998; Özdemir and Devres, 1999).

4 Results and discussion

4.1 Drying characteristics

Figures 3, 4 and 5 reveal the effect of air temperature on the drying curve of taro. It was noticed that the drying of taro occurred under the falling rate period. This refers that effective moisture diffusivity is the most likely dominant physical mechanism which causes the driving of moisture from taro samples. Similar outcomes were also stated by Akpinar and Bicer (2008) for long green pepper, Doymaz (2005) for okra, Tunde-Akintunde and Afon (2010) for cassava, and Agarry and Owabor (2012) for banana. It is obvious from Figs. 3-5 that at the initial stage of drying, the drying rate was very rapid and gradually decreased throughout the drying period. These findings may be due to the higher initial moisture content of taro which contributed to the effortless moisture liberation and the reduction in drying rate as drying process advances due to the harder and shrinkage product surface.

4.2 Influence of drying air temperature

It is apparent from Figures. 3-5 that the drying rate of taro increases with the increase of drying temperature. The time required to reduce the moisture content of taro from 86% ± 0.5% (w.b) to a final 6% ± 0.5% was 840 min at 50°C, 600 min at 60°C and 510 min at 70°C, respectively. Drying process was significantly prompted by the drying air temperature as moisture ratio decreased rapidly with increased temperature. Several researchers reported that the drying rate increased with the increase in drying air temperature for drying of various vegetables such as okra (Doymaz, 2005), garlic (Madamba et al., 1996), and eggplant (Ertekin and Yaldiz, 2004).

4.3 Evaluation of the thin layer drying models

The empirical drying constant (a) and drying rate constant (k) and coefficient of determination (R^2) for taro roots at each drying temperature are presented in Table 1. For all the drying experiment the coefficient of determination ranged from 0.98093 to 0.99986. All the drying models at 60°C and 70°C gave the value of coefficient of determination greater than 0.99 while the R^2 values of Page equation for each drying temperature greater than the 0.999. These high coefficients of determination are due to the highly linear plots of all the unaccomplished moisture content, which are perhaps due to equilibrium moisture content.

Statistical parameters as RMSE, χ^2 and percent error (PE) were given in Table 2 for all the drying model at each drying temperature. It is clear from the statistical analysis that all drying model predict the good drying behavior of taro root as the RMSE value ranged between 0.03 and 0.008 for the Henderson-Pabis model, between 0.004 and 0.009 for the Page model, and between 0.007 and 0.04 for the Lewis model, respectively. The selected drying model represented the experimental values satisfactory as had an error below 5%. However, the Page model was better fit for the drying of taro root in contrast to the Henderson-Pabis model and Lewis model. Similar findings were also reported by Madamba et al. (1996) for garlic slices, by Doymaz and Pale (2002) for red pepper and by Doymaz (2005) for okra.

Table 1 Empirical constant of the Henderson-Pabis, Page and Lewis equations

Temp (^oC)	Henderson-Pabis			Page equation			Lewis equation	
	k (min^{-1})	a	R^2	k (min^{-1})	a	R^2	k (min^{-1})	R^2
50	0.0033	1.08317	0.98884	5.70521E-4	1.28356	0.99986	0.00305	0.98093
60	0.00434	1.04432	0.99593	0.0018	1.14888	0.99952	0.00414	0.99338
70	0.00684	1.01147	0.99915	0.00601	1.02271	0.99912	0.00676	0.99904

Table 2 Model prediction evaluation

Temp (^oC)	Henderson-Pabis			Page equation			Lewis equation		
	χ^2 (10^{-5})	RMSE	%PE	χ^2 (10^{-5})	RMSE	%PE	χ^2 (10^{-5})	RMSE	%PE
50	100.0	0.03	4.26	1.35	0.004	1.56	179.0	0.04	3.64
60	3.54	0.005	2.85	4.16	0.006	1.83	5.77	0.007	2.73
70	7.33	0.008	2.92	7.56	0.009	1.94	8.27	0.01	2.28

4.4 Calculation of effective moisture diffusivity and activation energy of taro roots

Effective moisture diffusivity of taro root at different temperature was calculated as stated in article 2.2 depicted in Figure 6. It is also evident from Figure 4 that the values of effective moisture diffusivity were linearly proportional with the increased temperature. These findings may be due to the rapid diffusion of moisture to the surface that at high temperature more thermal energy is transferred to the food product that causes rapid heating, thereby the vapor pressure inside the product increased.

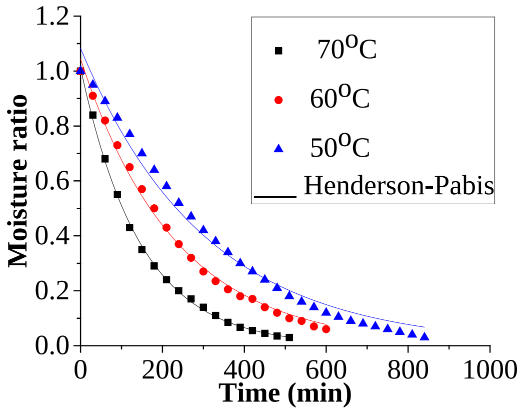

Figure 3 Experimental and computed moisture ratio obtained from Henderson-Pabis model

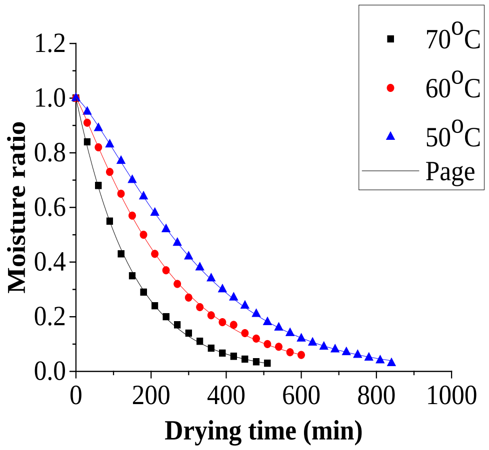

Figure 4 Experimental and computed moisture ratio obtained from Page model

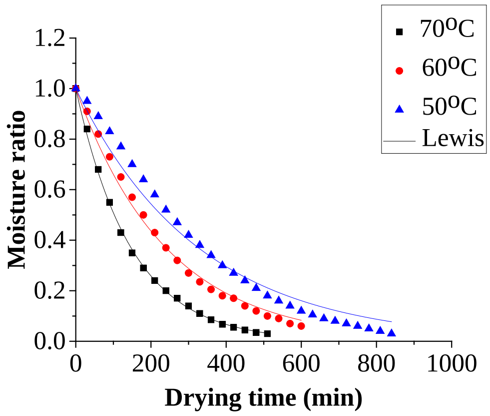

Figure 5 Experimental and computed moisture ratio obtained from Lewis model

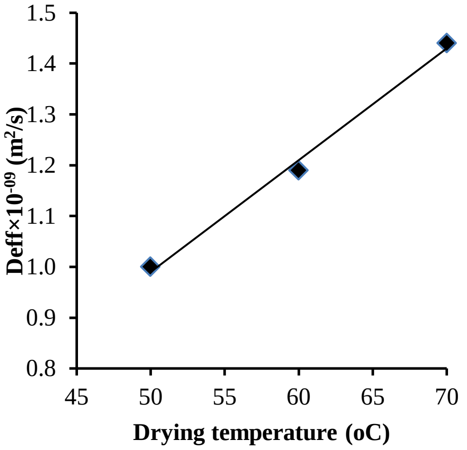

Figure 6 Effective moisture diffusivity

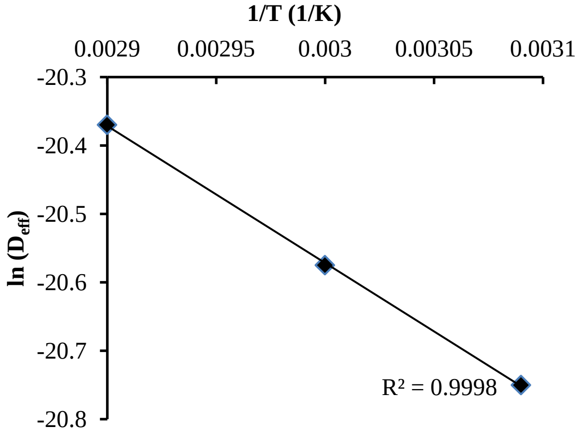

Figure 7 Activation energy at different temperature

The values of effective moisture diffusivity of this study were paralleled with the general ranged of 10^{-11} to 10^{-8} m^2 s^{-1} for the drying of overall food materials (Sacilik et al., 2006; Lee and Zuo, 2011). The graph in Figure 6 shows that the values of D_{eff} increased with the increase of drying temperature. Several researchers were also reported similar findings (Rahman and Kumar, 2007; Sobukola, 2009; Kadam et al., 2011; Khawas et al., 2014).

The activation energy of taro roots was calculated from the slope of Figure 7 based on the theoretical aspects that described in section 2.2. Activation energy for moisture diffusion for this present study is 18.03 kJ mol^{-1}. Activation energy for the present study was lower comparing the reported values on different vegetables (Gupta et al., 2002; Senadeera et al., 2003; Doymaz, 2004; Park et al., 2002). These variations in activation energy may be attributed to the differences in chemical composition and structure of the raw material undergoing drying.

5 Conclusion

Drying kinetics of taro roots were experimentally investigated in a laboratory scale hot air dryer at 50°C, 60°C and 70°C. Drying process of taro roots took place in falling rate period. Thin layer mathematical drying model were fit with the experimental data to describe the drying behavior of taro root. Page model at 50°C aptly describes the drying characteristics of taro roots. The effective moisture diffusivity for taro roots ranged from 9.91×10^{-10} to 1.47×10^{-9} m^2 s^{-1} while dried between 50°C-70°C. Activation energy for the present study was 18.01 kj mol^{-1}.

References

Afolabi, T. J. 2014. Thin layer drying kinetics and modeling of okra (Abelmoschus Esculentus (L.) moench) slices under natural and forced convection air drying. *Food Science and Quality Management*, 28(6): 35-47.

Agarry, S. E. 2016. Modeling the thin layer drying kinetics of untreated and blanch-osmotic pre-treated tomato slices. *Turkish journal of Agriculture- Food Science and Technology*, 4(10): 850-858.

Agarry, S. E., A. O. Ajani, and M. O. Aremu. 2013. Thin layer drying kinetics of pineapple: effects of blanching temperature-time combination. *Nigerian Journal of Basic and Applied Sciences*, 21(1): 1-10.

Agarry, S. E., and C. N. Owabor. 2012. Modelling of the drying kinetics of banana under natural convection and forced air drying. *Journal of Nigerian Society of Chemical Engineers*, 27(1): 101-115.

Agbor-Egbe, T. 1991. Study on the factors affecting storage of edible aroids. *Annals of Applied Biology*, 119(1): 121-130.

Akpinar, E. K., and Y. Bicer. 2008. Mathematical modeling of thin layer drying process of long green pepper in solar dryer and under open sun. *Energy Conversion and Management*, 49(6): 1367–1375.

Baidoo, E. A., P. T. Akonor, and C. Tortoe. 2014. Effect of pre-treatment and storage condition on the physicochemical properties of taro (*Colocasia esculenta* [L.] Schott) Flour. *International Journal of Food Science and Nutrition Engineering*, 4(4): 91-97.

Basunia, M. A., and T. Abe. 2001. Thin layer solar drying characteristics of rough rice under natural convection. *Journal of Food Engineering*, 47(4): 295–301.

Bruce, D. M. 1985. Exposed-layer barley drying, three models fitted to new data up to 150°C. *Journal of Agricultural Engineering Research*, 32(4): 337–347.

Crank, J. 1975. *The Mathematics of Diffusion*. Oxford: Clarendom Press.

Dandamrongrak, R., G. Young, and R. Mason. 2002. Evaluation of various pre-treatments for the dehydration of banana and selection of suitable drying models. *Journal of Food Engineering*, 55(2): 139–146.

Darkwa, S., and A. A. Darkwa. 2013. TARO “Colocasia esculenta”: It’s Utilization in Food Products in Ghana. *Food Processing and Technology*, 4(5): 1-7.

Darvish, H., A. Banakar, and M. Zarein. 2012. Mathmatical modeling and thin layer drying kinetics of carrot slices. *Global Journal of Science Frontier Research*, 127(7): 57-64.

Doymaz, I. 2004. Convective air drying characteristics of thin layer carrots. *Journal of Food Engineering*, 61(3): 359–364.

Doymaz, I. 2005. Drying characteristics and kinetics of okra. *Journal of Food Engineering*, 69(3): 275-279.

Doymaz, I., and M. Pala. 2002. Hot-air drying characteristics of red pepper. *Journal of Food Engineering*, 55(4): 331–335.

Ertekin, C., and O. Yaldiz. 2004. Drying of eggplant and selection of a suitable thin layer drying model. *Journal of Food Engineering*, 63(3): 349–359.

FAO. 1999. *Taro Cultivation in Asia and the Pacific*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

Feng, H., J. Tang, and I. Dixon-Warren. 2000. Determination of moisture diffusivity of red delicious apple tissues by thermogravimetric analysis. *Drying Technology*, 18(6): 1183 -1199.

Gupta, P., J. Ahmed, U. S. Shivhare, and G. S. V. Raghavan. 2002. Drying characteristics of red chilli. *Drying Technology*, 20(10): 1975–1987.

Jane, J., L. Shen, J. Chen, S. Lim, T. Kasemsuwan, and W. K. Nip. 1992. Physical and chemical studies of taro starches and flours. *American Association of Cereal Chemists*, 69(5):528-535.

Kadam, D. M., R. K. Goyal, K. K. Singh, and M. K. Gupta. 2011. Thin layer convective drying of mint leaves. *Journal of Medicinal Plant Research*, 5(2): 164-170.

Kamalakar, D., L. N. Dr. Rao,P. R. Kumar, and M. V. Dr. Rao. 2014. Drying characteristics of red chillies: mathematical modelling and drying experiments. *International Journal of Engineering Sciences and Research Technology*, 3(7): 425-437.

Kaushal, P., V. Kumar, and H. K. Sharma. 2012. Comparative study of physicochemical, functional, antinutritional and pasting properties of taro (*Colocasia esculenta*), rice (*Oryza sativa*) flour, pigeonpea (*Cajanus cajan*) flour and their blends. *LWT-Food Science and Technology*, 48(1): 59-68.

Kaushal, P., and H. K. Sharma. 2013. Convective dehydration kinetics of noodles prepared from taro (*Colocasia esculenta*), rice (*Oryza sativa*) and pigeonpea (*Cajanus cajan*) flours. *CIGR Journal*, 15(4): 2002-2012.

Khawas, P., A. J. Das, K. K. Dash, and S. C. Deka. 2014. Thin-layer drying characteristics of Kachkal banana peel (Musa ABB) of Assam, India. *International Food Research Journal*, 21(3): 975-982.

Kingsly, R. P., R. J. Goyal, M. R. Manikantan, and S. M. Ilyas. 2007. Effects of pretreatments and drying air temperature on drying behaviour of peach slice. *International Journal of Food science and Technology*, 42(1): 65-69.

Lebot, V. 2009. *Tropical Root and Tuber Crops: Cassava, Sweet Potato, Yams, Aroids.* Oxfordshire, UK: CAB International.

Lee, H. J., and L. Zuo. 2011. Mathematical modeling on vacuum drying of Zizphus jujube miller slices. *Journal of Food Science and Technology*, 50(1): 115–121.

Madamba, P. S., R. H. Driscoll, and K. A. Buckle. 1996. The thin layer drying characteristics of garlic slices. *Journal of Food Engineering*, 29(1): 75–97.

McLaughlin, C. P., and T. R. A. Magee. 1998. The determination of sorption isotherm and the isosteric heats of sorption for potatoes. *Journal of Food Engineering*, 35(3): 267–280.

McMinn, W. A. M. 2006. Thin-layer modeling of the convective, microwave, microwave convective and microwave-vacuum drying of lactose powder. *Journal of Food Engineering*, 72(2): 113–123.

Midilli, A., H. Olgun, and T. Ayhan. 1999. Experimental studies on mushroom and pollen drying. *International Journal of Energy Research*, 23(13): 1143–1152.

Mondal, M. H. T., K. S. P. Shiplu, K. P. Sen, J. Roy, and M. S. H. Sarker. 2019. Performance evaluation of small scale energy efficient mixed flow dryer for drying of high moisture paddy. *Drying Technology*, 37(12): 1541-1550.

Mujumbar, A. S. 1995. *Handbook of Industrial Drying*. 2nd ed. New York: Marcel Dekker.

Njintang, Y. N. 2003. Studies on the production of taro (Colocasia esculenta) flour for use in the preparation of achu-a taro base food. Ph.D. diss., University of Ngaounde´re´, Cameroun.

Nuh, D. N., and B. J. Brinkworth. 1997. A novel thin-layer model for crop drying. *Transactions of the American Society of Agricultural Engineers*, 40(3): 659-669.

Ochoa-Martinez, C. I., and A. A. Ayala-Aponte. 2009. Suitability of Crank’s solution to Ficks second law for water diffusivity calculation and moisture loss prediction in osmotic dehydration of fruits. *Journal of Food Process Engineering*, 32(6): 933-943.

Onwude, D. I., N. Hashim, R. B. Janius, N. Nawi, and K. Abdan. 2016. Evaluation of a suitable thin layer model for drying of pumpkin under forced air convection. *International Food Research Journal*, 23(3): 1173-1181.

Özdemir, M., and Y. O. Devres. 1999. The thin layer drying characteristics of hazelnuts during roasting. *Journal of Food Engineering*, 42(4): 225–233.

Pala, M., T. Mahmutoglu, and B. Saygi. 1996. Effects of pretreatments on quality of open-air and solar dried apricots. *Molecular Nutrition and Food Research,* 40(3): 137–141.

Pangavhane, D. R., R. L. Sawhney, and P. N. Sarsavadia, 1999. Effect of various dipping pretreatment on drying kinetics of Thompson seedless grapes. *Journal of Food Engineering*, 39(2): 211–216.

Park, K. J., Z. Vohnikova, and F. P. R. Brod. 2002. Evaluation of drying parameters and desorption isotherms of garden mint leaves (Mentha crispa L.). *Journal of Food Engineering*, 51(3): 193–199.

Parti, M. 1993. Selection of mathematical models for grain drying in thin-layers. *Journal of Agricultural Engineering Research*, 54(4): 339-352.

Prabhanjan, D. G., H. S. Ramaswamy, and G. S. V. Raghavan. 1995. Microwave-assisted convective air drying of thin layer carrots. *Journal of Food Engineering*, 25(2): 283–293.

Rahman, N., and S. Kumar. 2007. Influence of sample size and shape on transport parameters during drying of shrinking bodies. *Journal of Food Processing Engineering*, 30(2): 186 -203.

Roberts, J. S., D. R. Kidd, and O. Padilla-Zakour. 2008. Drying kinetics of grape seeds. *Journal of Food Engineering,* 89(4): 460-465.

Sabarez, H., W. E. Price, P. J. Back, and L. A. Woolf. 1997. Modeling the kinetics of drying of d'Agen plums (Prunus domestica). *Food Chemistry*, 60(3): 371–382.

Sacilik, K., R. Keskin, and K. A. Elicin. 2006. Mathematical modeling of solar tunnel drying of thin layer organic tomato. *Journal of Food Engineering*, 73(3): 231-238.

Senadeera, W., B. R. Bhandari, G. Young, and B. Wijesinghe. 2003. Influence of shapes of selected vegetable materials on drying kinetics during fluidized bed drying. *Journal of Food Engineering,* 58(3): 277-283.

Sobukola, O. 2009. Effect of pretreatment on the drying characteristics and kinetics of okra (Abelmoschus esculentus (L.) Moench) slices. *International of Journal of Food Engineering,* 5(2): 1556 –3758.

Sogi, D. S., U. S. Shivhare, S. K. Garg, and A. S. Bawa. 2003. Water sorption isotherm and drying characteristics of tomato seeds. *Biosystems Engineering*, 84(3): 297-301.

Tunde-Akintunde, T. Y., and A. A. Afon. 2010. Modeling of hot air drying of preheated cassava chips. *CIGR Journal,* 12(2): 34-41.

Wang, J. K. 1983. *Taro-A Review of Colocasia Esculenta and Its Potentials*. Honolulu: University of Hawaii Press.

Whitfield, E. D. 2000. Solar dryer systems and the internet: important resources to improve food preparation. In *Proceedings of the international Conference on Solar Cooking,* 26–29. Kimberly-South Africa, 26 November.

Yaldız, O., and C. Ertekin. 2001. Thin layer solar drying of some different vegetables. *Drying Technology*, 19(3): 583–596.