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Research Article

Kinetics and mathematical modeling of thin layer drying of mango leather

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Abstract

Mango is a major producing fruit in Bangladesh. According to the research, post-harvest loss of mango is about 34% of the total production. To reduce huge losses, leather production by drying is a good alternative. In this paper, the thin layer drying kinetics of formulated mango leather were studied at different temperatures (55, 60 and 65°C) and thicknesses (3mm and 5 mm). Drying time was decreased with increasing temperature and increased with increasing leather thickness. Seven different models (Lewis, Henderson and Pabis, Page, Modified Page, Logarithmic, Wang and Singh and Midilli et al.) were used to describe drying characteristics where all models were compared with coefficient of determination (R^2), reduced mean square of deviation (χ^2), mean bias error (MBE), root mean square error (RSME) and standard error of estimate (SEE). The Midilli et al. model was found to be best for describing thin layer drying of mango leather. According to Fick's diffusion model, the effective moisture diffusivities were between 2.17$\times 10^{-10}$ to 3.45$\times 10^{-10}$ m^2/s. The activation energy of moisture diffusion was estimated to be 41.8141 kJ/mol.

Keywords: *Mango leather, Drying kinetics, Thin layer drying models, Moisture diffusivity, Activation energy*

1. Introduction

Mango (Mangifera indica L.) is the most producing fruit of Bangladesh where annual production is 1162,000 tons (BBS, 2016). Currently, the country ranked 8th in the total world production of mango (FAO, 2016). Due to highly perishable in nature, a huge amount of mango is being spoiled in every year, mostly because of improper processing and preservation facilities. Average post-harvest loss of mango in Bangladesh is about 34% (Bhuiyan, 2011). Converting raw or ripe mangoes into leather by drying can be the easy and best way to minimize huge post-harvest loss of Bangladesh.

Mango leather is also known as mango bar or slab, is a chewy and flavored dehydrated confectionery item that is eaten like candy, snacks or dessert (Diamante *et al.,* 2014; Quintero Ruiz *et al.,* 2011). Mango pulp is mixed with sugar, gelatinizing agent (pectin or starch), acid, and then dehydrated into thin sheets to get mango leather (Diamante *et al.,* 2014; Gujral and Brar, 2003; Quintero Ruiz *et al.,* 2011). Commercially, potassium metabisulphite can be used to get better color, thus more consumer preference (Diamante *et al.,* 2014) where the use of hydrocolloids lower the drying rate of leather for initial two hours (Gujral and Khanna, 2002). In Bangladesh, the demand for mango leather increasing day by day due to its distinct flavor and sweet-sour test.

Convective dehydration of fruit leather is mostly referred by researchers over conventional sun drying as this method is hygienic, controllable and faster (Concha-Meyer *et al.,* 2016; Diamante *et al.,* 2014; Quintero Ruiz *et al.,* 2011; Valenzuela and Aguilera, 2015).

Mathematical drying models are very useful tool to describe the moisture removal of product to be dried. Models are very effective to know about variables in the process, drying kinetics prediction, and adjusting operating parameters (Rafiee and Meisami-asl, 2009). To overcome large-scale experimentation, models are the best mathematical tool to design the heat and mass transfer process to get the best quality final products (Chowdhury *et al.,* 2011; da Silva *et al.,* 2014; Marcel *et al.,* 2014). Mathematical modeling of thin layer drying of similar products has been studied by several researchers such as jackfruit leather (Chowdhury *et al.,* 2011), SMP and soy protein modified mango leather (Gujral and Khanna, 2002), hydrocolloid modified mango leather (Gujral and Brar, 2003), whole banana(da Silva *et al.,* 2014), sliced mango (Akoy *et al.,* 2008; Goyal *et al.,* 2006; Kabiru *et al.,* 2013; Marcel *et al.,* 2014), papaya leather (Chan and Cavaletto, 1978), sliced papaya (Yousefi, 2015). The page model was reported satisfactory for whole banana(da Silva *et al.,*

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2014) sliced mango(Akoy *et al.,* 2008; Goyal *et al.,* 2006; Kabiru *et al.,* 2013), the Midilli *et al.,* model for apple (Rafiee and Meisami-asl, 2009) and sliced ripened mango (Marcel *et al.,* 2014) where the modified page model reported as the best for thin layer dying of jackfruit leather (Chowdhury *et al.,* 2011). Cast-tape drying (da Silva Simão *et al.,* 2018) and microwave drying (Pushpa *et al*., 2006) were studied for sensory and quality evaluation of mango leather. However, no investigation has been found on mathematical modeling of most popular plain mango leather of Bangladesh.

The objectives of this study were: (a) to study the effect of temperature and leather thickness and (b) to investigate the suitable model of thin layer drying of formulated mango leather from Fazli variety.

2. Materials and method

2.1 Thin layer drying of mango leather

Fully ripened healthy mangoes (Fazli variety), collected from local market of Sher-e-Bangla Agricultural University were used for this study. Washed, peeled and destoned mangoes were chopped manually and blended (Model: STEELE-MG-172) to get the pulp. The strained mango pulp with total solid content of 13.7% was blanched at 92°C for 2 minutes with continuous stirring. Citric acid (0.6% w/w) and potassium metabisulphite (0.2%w/w) were added at the end of blanching process. The total solid content of the puree was increased to 35% by the addition of sugar. Then puree was sprayed to the stainless steel trays (51 cm × 23 cm) with plastic film and adjusted to 3mm and 5mm thicknesses. The trays were dried for 6 hours in a laboratory scale hot air cabinet (Model: TNH 11, China) at the temperature of 55, 60 and 65 (±1) °C, with an air velocity of 3.0 m/s. The dryer was heated at least 30 minutes for stabilizing the drying parameters. Moisture losses of the mango leathers were measured at 15 minutes intervals for initial 2 hours and then every 30 minutes up to end of drying. The drying was stopped when samples reached a no weight loss condition. All experiments were replicated three times and the average value was used for calculation.

2.2 Mathematical modeling of drying kinetics

Moisture ratio of all leather samples during drying is normally express in equation in equation in 1.

$$MR = (M_t - M_{eq})/(M_0 - M_{eq}) \tag{1}$$

Where MR stands for moisture ratio; M_t, $M_{eq.}$, and M_0 are the moisture content at time t, equilibrium moisture content and initial moisture content respectively.

Equation 1 can be simplified as follows (Doymaz, 2007; Goyal *et al.,* 2006; Rafiee and Meisami-asl, 2009)

$$\mathrm{MR} = \mathrm{M_t}/\mathrm{M_0} \tag{2}$$

Selected models for thin layer drying kinetics of mango leather is shown in table 1. Nonlinear regression was performed to solve the models.

Table 1: Selected models for describing thin layer drying kinetics of mango leather

Model name	Mathematical expression	Reference
Lewis	$MR = \exp(-kt)$	(Bruce, 1985)
Henderson and Pabis	$MR = \mathrm{a}\exp(-kt)$	(Henderson and Pabis, 1961)
Page	$MR = \exp(-kt^n)$	(Doymaz, 2007)
Modified page	$MR = \exp(-(kt^n))$	(Goyal *et al.,* 2006)
Logarithmic	$MR = \mathrm{a}\exp(-kt) + c$	(Pehlivan, 1974)
Wang and Singh	$MR = 1 + at + bt^2$	(Wang and Singh, 1978)
Midilli *et al.*	$MR = \mathrm{a}\exp(-kt^n) + bt$	(Midilli *et al.,* 2002)

The coefficient of determination (R^2), reduced mean square of deviation (χ^2), mean bias error (MBE), root mean square error (RSME) and standard error of estimate (SEE) were used as the parameters to select the best model for describing thin layer drying kinetics. The higher R^2 value and lower χ^2, MBE, RSME and SEE values were the main criteria for selecting best model (Ahmed *et al.,* 2018; Chowdhury *et al.,* 2011; Goyal *et al.,* 2006; Rafiee and Meisami-asl, 2009; Younis *et al.,* 2018). Statistical parameters for the goodness of fit can be calculated as follows:

$$\mathrm{R}^2 = \left[\frac{\left(\sum MR_{exp}\times MR_{pre}\right)^2}{\sum\left(MR_{exp}\right)^2\times\sum\left(MR_{pre}\right)^2}\right] \tag{3}$$

$$\chi^2 = \frac{\sum\left(MR_{exp}-MR_{pre}\right)^2}{N-z} \tag{4}$$

$$MBE = \frac{\sum\left(MR_{exp}-MR_{pre}\right)}{N} \tag{5}$$

$$RSME = \sqrt[2]{\left(\frac{\sum\left(MR_{exp}-MR_{pre}\right)^2}{N}\right)} \tag{6}$$

$$SEE = \sqrt[2]{\frac{\sum\left(MR_{exp}-MR_{pre}\right)^2}{df}} \tag{7}$$

Where MR_{exp}, MR_{pre}, N and z are the experimental moisture ratio, predicted moisture ratio, number of observation and number of drying constants respectively.

2.3 Effective moisture diffusivity and activation energy

The effective moisture diffusivity of mango leather can be interpreted by using Fick's second law of diffusion. Assuming uniform moisture content in surrounding bulk environment, negligible temperature gradient within the sample, negligible external resistance to moisture diffusion to the environment and constant diffusion coefficient at constant drying temperature, the Fick's law of diffusion for particles with slab geometry is defined as (Crank, 1975):

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

Here D_{eff} , L and t are the effective moisture diffusivity (m^2/s), slice thickness (m) and drying time (s) respectively. The equation 8 can be simplified to a straight line equation as follows:

$$\ln(MR) = ln\frac{8}{\pi^2} - \left(\frac{-\pi^2 D_{eff}}{L^2}\right) t \quad (9)$$

The effective moisture diffusivity was obtained from the slope of the plot of ln (MR) against time, t.

Where, slope $= \frac{-\pi^2 D_{eff}}{L^2}$

Temperature dependence of effective moisture diffusivity can be described by Arrhenius type equation(Aregbesola *et al.,* 2015; Islam, 1980; Moraes *et al.,* 2008) as follows:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT_{abs}}\right) \quad (10)$$

Where E_a, R and T_{abs} are the activation energy (kJ/mol), universal gas constant (kJ/mol.K) and absolute drying temperature (K).

Equation 10 can be arranged as:

$$\ln(D_{eff}) = \ln(D_0) - \left(\frac{E_a}{R}\right).\frac{1}{T_{abs}} \quad (11)$$

Where, slope $= -\frac{E_a}{R}$

The activation energy was calculated from the slope of the plot of $\ln(D_{eff})$ against inverse absolute temperature ($1/T_{abs}$).

3. Result and discussion

3.1 Drying kinetics of mango leathers

Drying curves of 3mm and 5mm thick mango leather at different temperatures are shown in figure 1 & 2. As seen from both figures moisture ratio decreases with the increase of drying time.

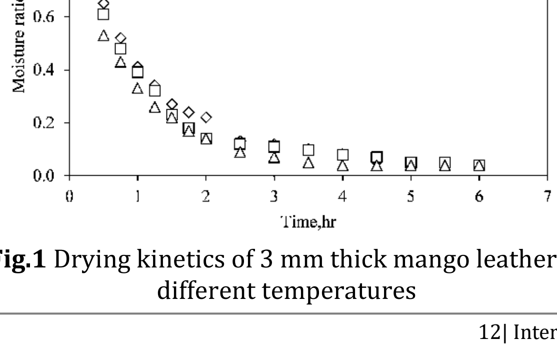

Fig.1 Drying kinetics of 3 mm thick mango leather at different temperatures

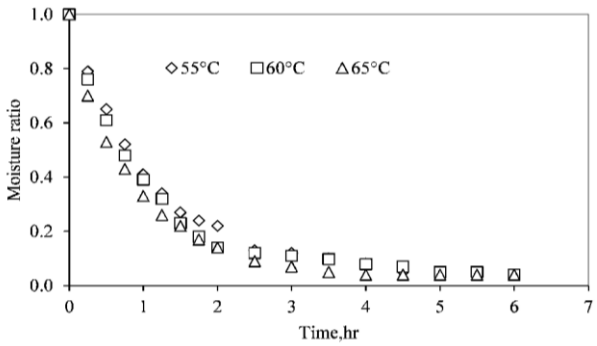

Fig.2 Drying kinetics of 5 mm thick mango leather at different temperatures

The significant influence of temperature in the drying of mango leather is also clear from figure 1 & 2. As expected, higher temperature gives shorter drying time thus lower moisture ratio compare to lower temperature. Similar drying trend reported for drying of jackfruit leather (Chowdhury *et al.,* 2011), raw mango slices (Goyal *et al.,* 2006) and garlic slices (Younis *et al.,* 2018).

Effect of leather thickness on drying time is also understandable from the comparison of figure 1 and figure 2. To dry a certain level of moisture ratio, longer time is required for higher thick leather. At temperature 65°C, 3mm thick mango leather required 2.5 hours to reach moisture ratio of 0.1 where 3 hours required for 5mm thick mango leather. The observed trend of this study is similar to results reported for thin layer drying of potato (Islam, 1980), apple (Rafiee and Meisami-asl, 2009) and raw mango (Kabiru *et al.,* 2013).

3.2 Mathematical modeling of drying curves

The experimentally obtained moisture ratio data of mango leathers at different drying temperature were fitted into selected thin layer drying models (Table 1). Non-linear regression analysis was used to get constants of all drying models. The calculated values of R^2, χ^2, MBE, RSME and SEE are presented in table 2. All models gave R^2 value of greater than 0.950. According to R^2 value and other statistical parameters, all selected models could adequately describe the thin layer drying of mango leathers. Nevertheless, the Midilli *et al.* and logarithmic models gave comparatively higher range of R^2 (0.9988 to 0.9997) and lower range of χ^2 (0.0001 to 0.0003), MBE (-0.0008 to 0.0088), RSME (0.0067 to 0.0141) and SEE (0.0076 to 0.0161) at temperature range 55 to 65°C. Therefore, according to statistical parameters, Midilli *at el.* followed by the logarithmic model was found as best to describe thin layer drying kinetics of mango leather. Similar result was reported for thin layer drying of sour cherry (Doymaz, 2007) and cassava pulp (Charmongkolpradit and Luampon, 2017).

Table 2: Values of statistical parameters of different thin layer drying models for mango leather

Model	Drying Temp., °C	R^2	χ^2	MBE	RSME	SEE
Lewis	55	0.9973	0.0006	0.0064	0.0223	0.0230
	60	0.9938	0.0011	0.0131	0.0319	0.0329
	65	0.9946	0.0009	0.0118	0.0285	0.0294
Henderson and Pabis	55	0.9975	0.0005	0.0074	0.0213	0.0227
	60	0.9940	0.0011	0.0141	0.0311	0.0331
	65	0.9950	0.0008	0.0131	0.0264	0.0281
Page	55	0.9974	0.0008	0.0050	0.0249	0.0264
	60	0.9961	0.0008	0.0110	0.0267	0.0284
	65	0.9978	0.0004	0.0021	0.0177	0.0189
Modified page	55	0.9974	0.0008	0.0059	0.0251	0.0267
	60	0.9961	0.0008	0.0107	0.0267	0.0284
	65	0.9978	0.0004	0.0021	0.0177	0.0189
Logarithmic	55	0.9994	0.0002	-0.0008	0.0112	0.0124
	60	0.9989	0.0002	0.0088	0.0141	0.0155
	65	0.9995	0.0002	0.00002	0.0105	0.0116
Wang and Singh	55	0.9640	0.0066	0.00001	0.0758	0.0807
	60	0.9824	0.0036	-0.0006	0.0542	0.0577
	65	0.9527	0.0075	0.00001	0.0813	0.0866
Midilli *et al.*	55	0.9994	0.0002	0.0002	0.0110	0.0126
	60	0.9988	0.0003	0.0005	0.0140	0.0161
	65	0.9997	0.0001	0.0001	0.0067	0.0076

Table 3: Constants and two fitting parameters of Midilli *et al.* model at different drying conditions

Temp. (°C) , thickness (mm)	a	k	n	b	R^2 (RSME)
55, 3	1.004	0.880	0.924	0.006	0.999 (0.011)
55, 5	0.998	0.590	1.021	0.007	0.999 (0.012)
60, 3	1.000	0.992	0.945	0.009	0.998 (0.015)
60,5	1.005	0.872	0.992	0.010	0.999 (0.012)
65,3	0.997	1.126	0.850	0.005	0.999 (0.005)
65,5	1.001	1.024	0.958	0.008	0.999 (0.008)

The constants of Midilli *et al.* model at different temperature and leather thickness is shown in table 3. According to statistical parameters, it was concluded that the Midilli *et al.* model is most appropriately predict the drying kinetics of mango leather at 65°C for both 3mm and 5mm thick leathers. The variation of experimental and predicted moisture ratio by Midilli *et al.* model at 65°C and leather thickness of 3 and 5 mm are depicted in figures 3-4. The experimental values are in excellent agreement with model predicted values.

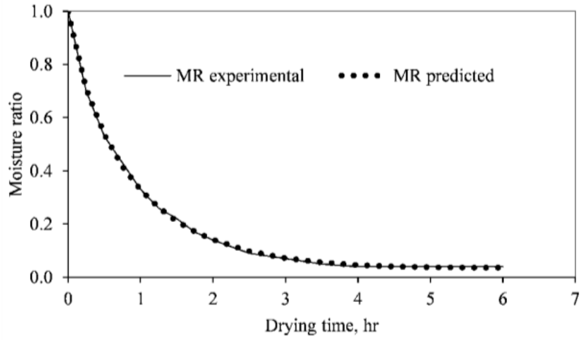

Fig.3 Variation of the experimental and predicted moisture ratio by Midilli *et al.* model at 65°C and 3mm leather thickness

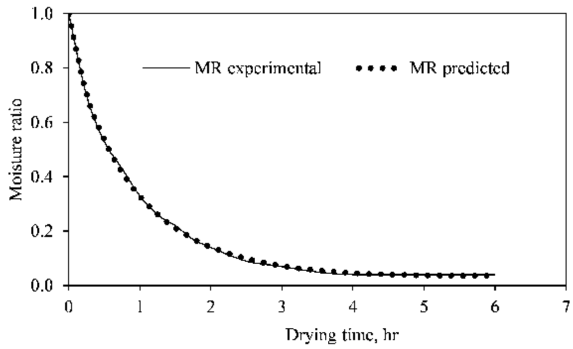

Fig.4 Variation of the experimental and predicted moisture ratio by Midilli *et al.* model at 65°C and 5mm leather thickness

3.3 Calculation of moisture diffusivity and activation energy

The effective moisture diffusivity is an important parameter to describe the mass transfer of moisture during the drying process. The values of D_{eff} were calculated as per equation (9) and shown in figure 5. The effective moisture diffusivity of mango leather was increased from 2.17×10^{-10} m^2/s at 55 °C to 3.45×10^{-10} m^2/s at 65°C. The D_{eff} value were found in the range of 2.62×10^{-10} to 3.19×10^{-10} m^2/s for raw mango slice (Goyal *et al.,* 2006) and 5.57×10^{-10} to

$4.75\times 10^{-10}\ m^2/s$ for pre-treated sour cherry (Doymaz, 2007) at the temperature range of 55 to 65 °C. The calculated data reveals that the effective moisture diffusivity increased with increasing drying temperature.

The value of activation energy (E_a) of mango leather during thin drying was obtained from the slope of figure 5.

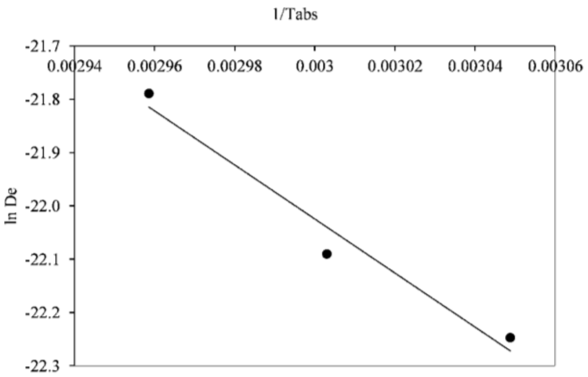

Fig.5 Influence of temperature on effective moisture diffusivity of mango leather

The calculated E_a value of mango leather was 41.81 kJ/mol. The value of activation energy of mango leather is close to 41.95 kJ/mol and 38.6 kJ/mol reported for red chili(Gupta *et al.,* 2002) and kiwi fruit (Orikasa *et al.,* 2008) respectively. The activation energy of mango slices was reported as 28.95 kJ/mol (Kabiru *et al.,* 2013).

Conclusion

Thin layer drying kinetics of formulated mango leather was investigated at different temperatures (55, 60 and 65°C) and leather thicknesses (3mm and 5mm). It was found that higher temperature gave lower moisture ratio, thus shorter drying time and greater leather thickness gave higher moisture ratio, thus higher drying time. The experimentally obtained moisture ratios were fitted with seven different thin layer drying models to explain drying kinetics of mango leather. According to statistical fitting parameters, as best, Midilli *et al*. model could be used to describe the drying behavior of mango leather. The effective moisture diffusivity increased from $2.17\times 10^{-10}\ m^2s^{-1}$ to $3.45\times 10^{-10}\ m^2s^{-1}$ following an Arrhenius type relationship with temperature. The activation energy of mango leather for moisture diffusion was 41.81 kJ/mol.

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References

Ahmed, M. W., Aziz, M. G. and Islam, M. N. (2018), Modeling of Moisture Adsorption Isotherm of Selected Commercial flours of Bangladesh', *The Agriculturists*, 16, 35–42.

Akoy, E. O. M., Hörsten, D. Von and Luecke, W. (2008), Drying Kinetics and Colour Change of Mango Slices as Affected by Drying Temperature and Time, *International Conference on Competition for Resources in a Changing World: New Drive for Rural Development*, Hohenheim, Germany, 1–6.

Aregbesola, O. A. *et al*. (2015) Mathematical modeling of thin layer drying characteristics of dika (Irvingia gabonensis) nuts and kernels', *Nigerian Food Journal,* 33, 83–89.

BBS (2016) Year Book of Agricultural Statistics of Bangladesh. Available at: www.bbs.gov.bd.

Bhuiyan, M. G. K., Rahman, A., Alam, M. M., Sarkar, K.M.A.S (2011), Post-Harvest Losses in Mango Value chain, I*nternational Journal of Bioresearch*, 10, 25-31.

Bruce, D. M. (1985), Exposed-layer barley drying: Three models fitted to new data up to 150°C, J*ournal of Agricultural Engineering Research*, 32, 337–348.

Chan, H. T. and Cavaletto, C. G. (1978), Dehydration and Storage Stability of Papaya Leather, *Journal of Food Science*, 43, 1723–1725.

Charmongkolpradit, S. and Luampon, R. (2017), Study of Thin Layer Drying Model for Cassava Pulp, *Energy Procedia,* 138, 354–359.

Chowdhury, M. M. I., Bala, B. K. and Haque, M. A. (2011), Mathematical modeling of thin-layer drying of jackfruit leather, *Journal of Food Processing and Preservation*, 35, 797–805.

Concha-Meyer, A. A. *et al*. (2016) 'Effect of storage on the physico-chemical and antioxidant properties of strawberry and kiwi leathers', Journal of Food Science, 81, 569–577.

Crank, J. (1975), The mathematics of diffusion. Oxford: Clarendon Press.

Diamante, L. M., Bai, X. and Busch, J. (2014), Fruit Leathers: Method of preparation and effect of different conditions on qualities, *International Journal of Food Science*, 2014.

Doymaz, I. (2007), Influence of pretreatment solution on the drying of sour cherry, *Journal of Food Engineering*, 78, 591–596.

FAO (2016), FAO Products Year Report. Rome. Available at: www.fao.org.

Goyal, R. K., Kingsly, A. R. P., Manikantan, M. R., Ilyas, S. M. (2006), Thin-layer Drying Kinetics of Raw Mango Slices, *Biosystems Engineering*, 95, 43–49.

Gujral, H. S. and Brar, S. S. (2003), Effect of hydrocolloids on the dehydration kinetics, color, and texture of mango leather, *International Journal of Food Properties*, 6, 269–279.

Gujral, H. S. and Khanna, G. (2002), Effect of skim milk powder, soy protein concentrate and sucrose on the dehydration behaviour, texture, color and acceptability of mango leather, *Journal of Food Engineering*, 55, 343–348.

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

Henderson, S. M. and Pabis, S. (1961), Grain drying theory. II: Temperature effects on drying coefficients, *Journal of Agricultural Engineering Research*, 6, 169–174.

Islam, M. N. (1980) Use of solar energy for development of self-stable potato products, *PhD Thesis*, Royal Veterinary and Agricultural University,Copenhagen, Denmark.

Kabiru, A. A., Joshua, A. A. and Raji, A. O. (2013), Effect of slice thickness and temperature on the drying kinetics of mango (mangifera indica), *Ijrras,* 5, 41–50.

Marcel, E., Balbine, M. and Alexis, K. (2014), Mathematical Modelling of Thin Layer Mangoes (Mangifera indica L .) Drying Process, *International Journal of Current Engineering and Technology*, 4, 3672–3676.

Midilli, A., Kucuk, H. and Yapar, Z. (2002), A new model for single-layer drying, *Drying Technology*, 20, 1503–1513.

Moraes, M. A., Rosa, G. S. and Pinto, L. A. A. (2008), Moisture sorption isotherms and thermodynamic properties of apple Fuji and garlic, I*nternational Journal of Food Science and Technology,* 43, 1824–1831.

Orikasa, T., Wu, L., Shiina, T. and Tagawa, A. (2008), Drying characteristics of kiwifruit during hot air drying, *Journal of Food Engineering,* 85, 303–308.

Pehlivan, D. (1974), Editorial: The Thyroid and Breast Cancer, *British Medical Journal*, 1(5906), 472.

Pushpa, G., Rajkumar, P., Gariepy, Y. and Raghavan, G. S. V. (2006), Microwave Drying of Enriched Mango Fruit Leather, *The Canadian Society for Bioengineering*, 1–11.

Quintero Ruiz, N. A., Demarchi, S. M. and Giner, S. A. (2011), Research on Dehydrated Fruit Leathers: A Review, *11th International Congress on Engineering and Food*, Food Process Engineering in a Changing World, 6.

Rafiee, S. and Meisami-asl, E. (2009), Mathematical Modeling of Kinetics of Thin-layer Drying of Apple (var. Golab. *Agricultural Engineering International: the CIGR Ejournal*, 11, 1185.

da Silva Simão, R. Moraes, J. O., Souza, P. G. (2018), Production of mango leathers by cast-tape drying: Product characteristics and sensory evaluation, LWT- Food Science and Technology, 99, 445–452.

da Silva, W. P., e Silva, C. M. D. P. S., Gama, F. J. A. and Gomes, J. P. (2014), Mathematical models to describe thin-layer drying and to determine drying rate of whole bananas, *Journal of the Saudi Society of Agricultural Sciences.* King Saud University & Saudi Society of Agricultural Sciences, 13, 67–74.

Valenzuela, C. and Aguilera, J. M. (2015), Effects of maltodextrin on hygroscopicity and crispness of apple leathers, J*ournal of Food Engineering,* 149, 51–60.

Wang, C. Y. and Singh, R. P. (1978), Use of variable equilibrium moisture content in modeling rice drying , *Trans. ASAE,* 11, 668–672.

Younis, M., Abdelkarim, D. and Zein El-Abdein, A. (2018), Kinetics and mathematical modeling of infrared thin-layer drying of garlic slices, *Saudi Journal of Biological Sciences,* 25, 253–258.

Yousefi, A. R., Aghdam, S. K., Chenar, M. P. and Niakousari, M. (2015), The Kinetics of Forced Convective Air-drying of Papaya (Carica papaya L .) Slices Pretreated in Osmotic Solution, *Iranian Food Science and Technology Research Journal, 9*, 270-278.