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Mathematical modelling and convective drying kinetics of osmotically dehydrated banana slices

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Abstract
Osmotic dehydration is a process in which partial water is removed by immersion of water containing cellular solid in a concentrated aqueous solution of high osmotic media for a specific time and temperature. Preliminary trials were planned for finalizing the concentration of osmo-lyte (Sugar solution: 40, 50 and 60ºBrix) and temperature of syrup 35, 45 and 55°C. On the basis of sensory analysis, samples dried at 45°C with 60ºBrix sugar concentration was considered best. The osmotically dehydrated banana slices were further dried using convective dryer at four different drying temperatures of 50, 55, 60 and 65°C at constant air velocity of 2.0 (± 0.1) m/s. In order to select the appropriate drying model, five mathematical drying models were fitted to the experimental data. Results indicated that moisture content of the product was reduced exponentially with drying time and no constant rate period was observed. Mathematical models were fitted to the experimental data and the best model was chosen as one with the highest coefficient of correlation (R^2) and the least reduced chi-square (χ^2), root mean square error (RMSE) and mean bias error (E_{MB}). The Page model gave the best results for describing the drying behaviour of osmotically dehydrated banana slices. The minimum and maximum values of water activity and rehydration ratio for osmo-convectively dried banana slices were found in the range of 0.268 to 0.322 and 1.4516 to 1.5461 for 50 and 65 ºC drying air temperatures, respectively.

Keywords: Banana, osmotic dehydration, convective drying, mathematical modelling, quality evaluation

1. Introduction

Banana is the most popular fresh fruit all over the world and its name comes from the Arabic word 'banan', which means finger. The scientific name of banana is *Musa acuminata* and *Musa balbisiana*. It is the 5th most important crop in world export trade after coffee, cereals, sugar and cocoa (Aurore *et al.*, 2009) [3].

Drying preserved food quality and food stability by lowering the water activity. Drying causes many physical, chemical and biochemical changes in the processed material. Pre-treatments often minimize the adverse changes occurring during dehydration and subsequent storage. The physical changes affecting dried food quality are shrinkage of cells, loss of rehydration ability, wet ability and case hardening. There are many advantages of fruit drying, such as: the inhibition of the growth of microorganisms and deterioration reactions by the water activity reduction (Caccavale *et al.,* 2016) [5] as well as the reduction of transport and storage costs due to weight and volume decrease (Tzempelikos *et al.,* 2015).

Osmotic dehydration is immersion in a hypertonic aqueous solution leading to a loss of water through the cell membranes of the product and subsequent flow along the inter-cellular space before diffusing into the solution. The osmotic process reduces energy consumption and improves food quality. The osmotic pre-treatment, prior to convective drying is an added complexity to the process design and control, due to the biological tissue change caused by pre-treatment. Convective drying is the process of removing water with air via simultaneous heat, mass and momentum transfer. The required heat energy is transferred to the surface of the product by convection and then is transferred inside the product by diffusion or convection, depending on the product structure. This heat flux causes a product temperature increase and moisture evaporation (Bezerra *et al*., 2015) [4].

Modelling of drying processes and kinetics is a tool for process control and necessary to choose suitable method of drying for a specific product. The developed models fall into three categories namely the theoretical, semi-theoretical and empirical. Semi-theoretical models offer a compromise between theory and ease of application (Khazaei & Daneshmandi, 2007) [11].

Semi-theoretical models are Lewis, Page, Henderson and Pabis, logarithmic, two terms exponential; models are used widely for designing as well as selection of optimum drying conditions and for accurate prediction of simultaneous heat and mass transfer phenomena during drying process. It also leads to produce the high quality product and increases the energy efficiency of drying system. Semi-theoretical models such as Page, Henderson and Pabis and logarithmic models are only valid under the drying and product conditions for which these models were developed. Thin-layer drying models have been used to describe the drying process of several agricultural products.
The goal of this work was the study of the influence of variables as temperature, fruit shape, osmosis and cultivar in drying kinetics of bananas Cv. Grand Naine, in a natural convection tray dryer. A mathematical model was applied to fit the drying kinetics.

2. Material and Methods

2.1 Osmotic treatment of banana

The banana samples were cut into slices of a uniform thickness of 2 cm. The preliminary experiments were planned for finalizing the concentration of osmo-lyte (sugar solution). Different concentrations of sugar solutions (40, 50 and 60ºBrix) were used for the osmotic pre-treatment of banana samples. Further, the osmotically pre-treated banana samples were dried at 35, 45 and 55ºC which was analyzed using sensory analysis. On the basis of which sample dried at 45 ºC with 60ºBrix sugar solution was considered the best.

2.2 Drying experiments

The convective-drying of osmotically dehydrated banana samples was carried out in a tray dryer at air temperatures of 50, 55, 60 and 65ºC at constant air velocity of 2.0 m/s. The samples were weighed at the start of the experiment and then after every 10 min intervals. At the end of each drying experiments, the final moisture content of the samples was determined as per AOAC, 2000 [1].

2.3 Mathematical modelling

Thin layer equations aimed to describe the drying phenomena, have been used to estimate drying times for several products and to access drying curves. Thin layer drying equations are important tools in mathematical modelling which describe the drying phenomena in a unified way, regardless of the controlling mechanism. Thin-layer drying models are generally based on liquid diffusion theory and the process can be explained by Fick's second law. Several thin layer equations, varying widely in nature, are available in the literatures that successfully explain the drying of several agricultural products. The drying kinetics was monitored and data were expressed in dimensionless variable moisture ratio. The moisture ratio (MR) of banana samples during drying experiments was calculated using the following equations:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

Where M_t is the moisture content at time t (db), M_o is the initial moisture content (db), and M_e is the equilibrium moisture content (db).
The instantaneous drying rate (DR) of banana samples was calculated from the drying data by estimating the changes in moisture content, which occurred in each consecutive time interval and was expressed as g water/g dry matter per minute. The drying rate of the sample was calculated by following the mass balance equation (Brooker *et al.*, 1974) as,

$$DR = \frac{\text{WML (g)}}{\text{Time interval (min) x DM (g)}} \quad (2)$$

Where,
R = Drying rate at time θ, g water/ g, min
WML = Initial weight of banana sample – Weight of sample after time θ

2.4 Adequacy of model fitting

To select a suitable model for describing drying process of banana samples, drying curves were fitted to thin layer drying equations (Table 1). In addition to R^2 (coefficient of determination), various statistical parameters such as reduced chi-square (γ^2) and root mean square error (RMSE) were also used as primary criterion to select the best equation. Root mean square error (RMSE) gives the deviation between the predicted and experimental value which was calculated as follows:

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

$$\alpha^2 = \sum_{i=1}^{N} \frac{(MR_{exp,i} - MR_{pre,i})^2}{N-n} \quad (4)$$

Where MR_{exp}, *i* is the experimentally observed moisture ratio, MR_{pre}, *i* is the predicted moisture ratio, *N* is the number of observations and *n* is the number of constants.

Table 1: Models used to describe drying of banana slices

Model equation	Name of model	Reference
MR = exp (-kt)	Exponential	Liu and Bakker-Arkema (1997) [14]
MR = exp ($-kt^n$)	Page	Page (1949) [15]
MR = a exp (-kt)	Henderson and Pabis	Henderson and Pabis (1961) [9]
MR = a + b *ln* (t)	Logarithmic	Chandra and Singh (1995) [6]
MR = At^B	Power law	Chandra and Singh (1995) [6]

2.5 Rehydration ratio

Rehydration ratio of banana samples was assessed by the method suggested by Jokic *et al.* (2009) [10]. Approximately 3 g of dried sample was placed in a 250 ml laboratory glass beaker (two analyses for each sample), 150 ml distilled water was added and the glass beaker was covered and heated to boil within 3 min. The content of the laboratory glass was then gently boiled for another 10 min and then cooled. The cooled content was filtered for 5 min under vacuum and weighed. The rehydration ratio was calculated as:

$$RR = \frac{W_R}{W_D} \quad (5)$$

Where
W_r = drained weight (g) of the rehydrated sample
W_d = weight of the dry sample used for rehydration.

2.6 Water activity

Moisture plays an important role in the stability of fresh, frozen and dried foods. Water activity can be defined as the ratio of the vapour pressure exerted by the food to the saturated vapour pressure of water at the same temperature.

$$aw = \frac{P_A}{P_{ASAT}} \quad (6)$$

Where
P_A = Vapour pressure of water exerted by food,
P_{Asat} = Saturated vapour pressure of water at the same temperature

2.7 Statistical analysis
The non-linear regression analysis of the experimental data was carried out by the software Statistic (13.0) for checking the validity of models.

3. Results and Discussion
The osmotic drying experiments followed by convective drying were performed on a ripe banana. In this process, bananas were cut into slices of approximately 2 cm in size. The banana slices were immersed in sugar solution of 40, 50 and 60ºBrix for about five hours, at three different osmotic temperatures 35, 45 and 55ºC. On the basis of sensory analysis, samples dried at 45°C with 60ºBrix sugar concentration was considered best. The osmotically dried banana samples were loaded on the perforated trays, weighed and kept into the convective dryer for further drying and the drying data were recorded at regular interval until completion of the experiment.

3.1 Effect of drying temperature on drying time and drying rate of banana
The average initial moisture content of osmotically dried ginger treated banana slices was 215.84 per cent (db). The typical curves showing variation in moisture content, drying rate and moisture ratio with drying time for osmo-convectively dried banana slices at an air temperature of 50, 55, 60 and 65 ºC are shown in Fig. 1, 2 and 3, respectively. Drying was continued until constant moisture content was reached. Increasing the drying temperature decreased the total drying time since heat transfer increased. The rate of moisture loss was higher at higher temperatures and the total drying time was reduced substantially with the increase in air temperature. The drying curve (Fig. 2) indicates that drying rate of different banana samples occurred in falling rate period without occurrence of constant rate during drying. The absence of constant rate convective drying may be due to that the sample could not provide constant supply of water for an appreciable period of time. Arumuganathan *et al.* (2009) [2] reported the occurrence of only falling rate period during drying of mango slices and milky mushroom. As the temperature was increased from 50, 55, 60 and 65 ºC the drying time was decreased. The results indicated that diffusion is the most likely physical mechanism governing moisture movement in the banana samples.

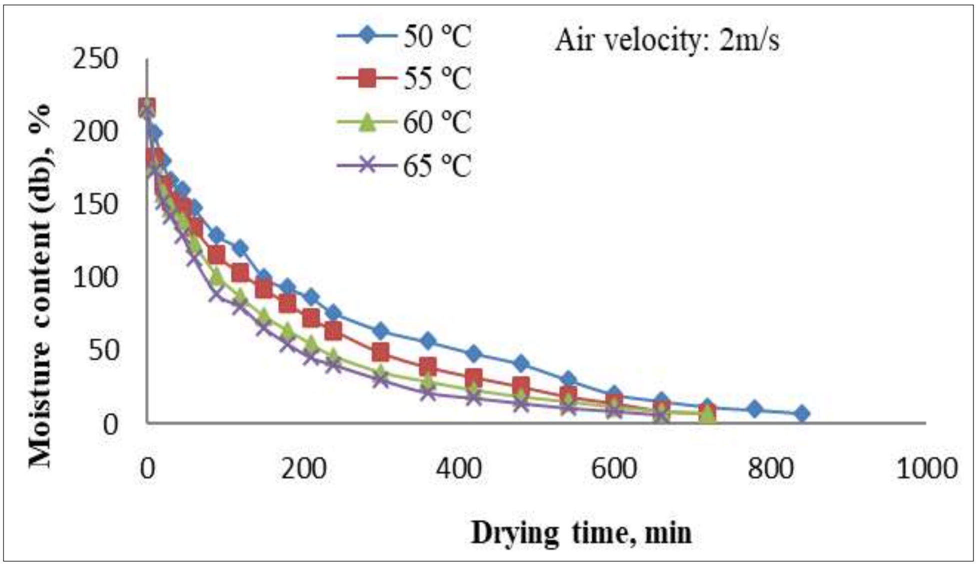

Fig 1: Drying curves of osmotically dehydrated banana at different temperatures.

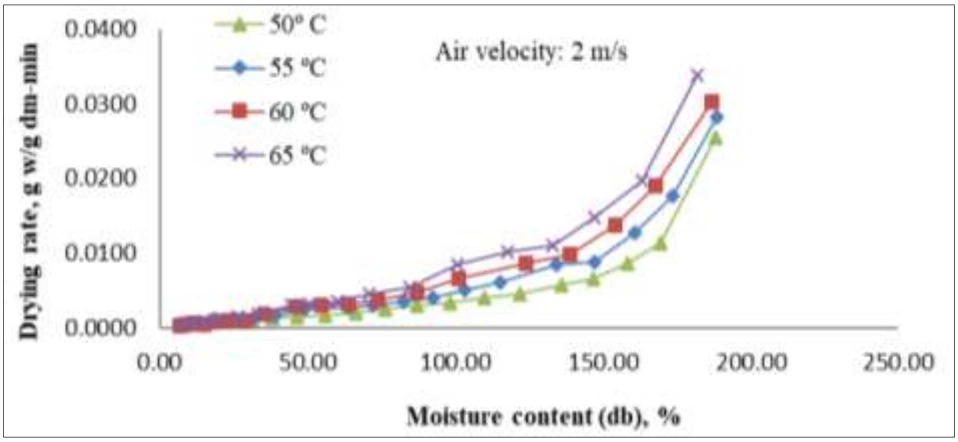

Fig 2: Drying rate versus drying time of osmotically dehydrated banana samples at different temperatures.

It can be seen that at higher moisture content, the increase in temperature has a more considerable effect on the drying rates as compared to lower temperatures, which is almost negligible toward the end (Fig. 2). It was further observed that the drying rate or moisture loss was faster at the beginning. The reduction in drying rate with progression of drying process may be due to the reduction in the available moisture and due to the development of case hardening. Reduction of drying rate might also be due to the development of the shrinkage which causes the reduction in porosity of the banana samples with advancement of the drying process. Kohli *et al*. (2018) [13] also reported the reduction in the drying rate at the end of drying of asparagus root due to the reduction in moisture availability with advancement of drying.

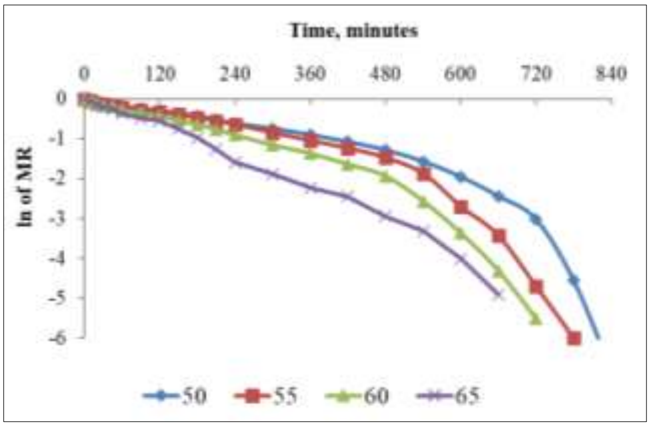

Fig 3: Moisture ratio versus drying time of osmotically dehydrated banana samples at different temperatures.

The moisture ratio (MR) is essential to describe different thin layer drying models. The moisture ratio reduced exponentially as the drying time increased (Doymaz, 2007) [8]. Continuous decrease in moisture ratio indicates that diffusion has governed the internal mass transfer. It can be anticipated that moisture ratio (MR) is reduced during drying process at all temperatures investigated in this study but at higher temperature (65 ºC) this reduction was quicker (Fig. 3). This can be attributed to a high rate of evaporation from the surface of banana samples at higher temperatures which leads to higher mass transfer rate. A higher drying air temperature decreased the moisture ratio faster due to the increase in air heat supply rate to the banana samples and the acceleration of moisture migration (Demir *et al.*, 2004) [7].

3.2 Validity of various mathematical models for convective drying of banana

Table 2 shows the statistical results of R^2, RMSE, γ^2 and E_{MB} of selected drying models. The highest values of R^2 and lowest RMSE, E_{MB} and γ^2 values were selected as optimal criteria in order to evaluate the fitting quality of 5 models proposed. It was observed that in all cases, the values of R^2 were greater than 0.90, indicating a good fit (Revaskar *et al.*, 2014) [17] except for power law model. However, the Page model gave comparatively higher R^2 values in all the drying treatments (0.9471-0.9813) and also the γ^2 (0.00012–0.00055), E_{MB} (0.00003–0.00013) and RMSE (0.00016–0.0072) values were lower. Hence, the Page model may be assumed to represent the thin-layer drying behaviour of banana slices. Kohli *et al*. (2017) [13] and Revaskar *et al.* (2014) [17] reported a similar result for air-drying of asparagus roots and onion slices, respectively.

Table 2: Different models and their constants and statistical parameters used in convective drying of osmotically dehydrated banana slices at various air temperatures

Models	Temperature	Constants				Statistical parameters			
	(ºC)	k	n	A	b	α^2	RMSE	E_{MB}	R^2
Exponential Model	50	0.0040				0.000581	0.02369	0.00056	0.9046
	55	0.0050				0.000862	0.02869	0.00082	0.9132
	60	0.0050				0.000246	0.01522	0.00023	0.9335
	65	0.0060				0.000315	0.01721	0.00029	0.9477
Page Model	50	1.0275	0.0027			0.000174	0.00016	0.00013	0.9471
	55	1.0030	0.0034			0.000127	0.001110	0.00012	0.9582
	60	0.9977	0.0043			0.000055	0.00728	0.00005	0.9813
	65	0.9838	0.0049			0.000036	0.00556	0.00003	0.9765
Henderson and Pabis Model	50	0.0055		1.5768		0.003240	0.05427	0.00294	0.9083
	55	0.0051		1.3541		0.001551	0.03746	0.00140	0.9186
	60	0.0054		1.2350		0.000673	0.02461	0.00060	0.9335
	65	0.0059		1.2413		0.000838	0.02739	0.00075	0.9369
Logarithmic Model	50			1.778	-0.242	0.001992	0.04256	0.00181	0.9090
	55			1.721	-0.238	0.001861	0.04103	0.00168	0.9183
	60			1.718	-0.247	0.001797	0.04021	0.00161	0.9304
	65			1.670	-0.245	0.001694	0.03893	0.00151	0.9416
Power law Model	50			29.994	-0.903	0.022869	0.14418	0.02079	0.4487
	55			19.077	-0.805	0.013952	0.11235	0.01262	0.5624
	60			18.596	-0.825	0.011998	0.10391	0.01079	0.6247
	65			17.923	-0.826	0.011767	0.10261	0.01052	0.6238

3.3 Rehydration ratio of banana

The rehydration ratio determines the ability of the sample to regain the water without disintegration, which can be taken as a quality parameter. It was observed that with the increase in drying temperature (50-65 ºC), the rehydration ratio of banana samples increased (Table 3). The highest rehydration ratio (1.5461) was observed in the case of banana samples dried at 65 ºC whereas least (1.4516) was observed in the case of banana samples dried at 50 ºC. This may be due to the fact that a higher drying temperature may cause decrease in water content at a faster rate and brings more physico-chemical changes in the products, which led to increased rehydration ratio of dried samples.

Table 3: Rehydration ratio of osmotically treated and convectively dried banana sample

Drying method	Drying temperatures, ˚C	Rehydration ratio
Osmo-convectively dried banana sample	50	1.4516
	55	1.4774
	60	1.5214
	65	1.5461

3.4 Water activity
The water activities of osmo-convectively dried banana slices were found in between 0.268 to 0.322 (Table 4). It can be revealed that as the temperature increased, water activity decreased (Table 4). The highest water activity (0.322) was found for banana samples dried at 50 ºC whereas least (0.268) was examined for 65 ºC.

Table 4: Water activity of osmotically treated and convectively dried banana sample

Drying method	Drying temperatures, ˚C	Water activity
Osmo-convectively dried banana sample	50	0.322
	55	0.293
	60	0.279
	65	0.268

4. Conclusion
Preliminary trials were investigated for fixing the temperature and concentration of osmo-lyte (process temperature: 35, 45, 55 ºC and sugar solution: 40, 50 60 ºBrix) in osmotic dehydrator. The osmo-lyte concentration, dried at 45 ºC with 60 ºBrix was considered as the best on the basis of sensory analysis and selected for convective drying. The effect of temperature on drying kinetics of osmotically dehydrated banana slices in convective drying was examined in this study. Convective drying experiments showed an increase in temperature results in reduction in drying time. Drying of banana occurred only in the falling rate period, no constant rate period during convective drying was observed. Five thin-layer drying models were investigated for their suitability to describe the drying kinetics of osmotically dehydrated banana slices. Among the empirical models applied to the experimented data, the page model best describes the convective drying characteristics of osmotically dehydrated banana slices, as it gave the good fit with high value for the coefficient of determination (R^2) and least reduced chi-square (γ^2), mean bias error (E_{MB}) and root mean square error (RMSE) values. It was found that with the increase in drying temperature from 50, 55, 60 to 65 ºC, the rehydration weight of osmotically dehydrated banana samples increased. While, the values of water activity decreased.

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