Development of empirical expression for thin layer groundnut drying under open sun and forced convection modes

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Abstract: The thin layer drying behaviour of groundnut was investigated under open sun drying (OSD) and indoor forced convection drying (IFCD) modes. The groundnut samples were dried from initial moisture content of 38% (w.b.) to the safe storage moisture content of 8%-10% (w.b.). Four mathematical models were compared for describing the groundnut drying process. The performance of thin layer drying models was investigated by comparing the statistical parameters such as coefficient of correlation (R), reduced chi-square (χ^2), root mean square error ($RMSE$), and mean bias error (MBE) between experimental and predicted moisture ratios. Henderson and Pabis model was observed to give the highest value of R and lowest values of χ^2, $RMSE$ and MBE for the groundnut drying under both OSD and IFCD modes. The values of statistical parameters under Lewis model were also found to be very close to Henderson and Pabis model. Therefore, Henderson and Pabis and Lewis models were found to be the best for describing the drying behaviour of groundnut under both given conditions.

Keywords: groundnut/peanut, thin layer, mathematical modelling, open sun drying, indoor forced convection drying, moisture ratio

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1 Introduction

Peanut (Groundnut), highly rich in protein (20% to 50%), fat (40% to 50%) and edible oil (43% to 55%), belongs to the bean family (Sahdev et al., 2016). It is one of the most important oilseed crop in India. It was considered to be originated in South America and then spread to other countries in the world (Zhao et al., 2012). It came into existence in India in the sixteenth century. It is also known as wonder nut, monkey nut and cashew nut for the poor people because of its highly nutritious values (Talawar, 2004).

Indian groundnut is very famous because of its taste, flavour and crunchiness. India contributes 14.83% share of groundnut production in the world (USDA, 2017) and ranks second (6.3 metric million tons) in the production of groundnut followed by China (17 metric million tons). Exports of Indian groundnuts have reached about 5.38 metric million tons during 2015-2016 (APEDA, 2017).

Groundnuts, just after harvesting, are required to be dried to its safe storage moisture level of 8%-10% for longer shelf life (Sahdev et al., 2015). In developing countries, farmers dry groundnuts by spreading under solar radiations in their fields just after harvesting. Drying (moisture removal process from the interior of the product) is one of the most important post-harvest processes to hinder the growth of fungi. Open sun drying (OSD) is the cheapest and most common method of drying agricultural products, but it involves many disadvantages such as deterioration of products due to dust, dirt, uncontrolled heating, discolouring of products because of Ultra-Violet rays, animals, microorganisms and so on. Post-harvest losses of the agricultural products

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are also estimated to be about 30%-40% due to improper method of drying (Sahdev et al., 2017). Moreover, farmers are also lacking with the better drying facilities. Hence, the need is felt to adopt such a method which gives continuous and controlled drying. Therefore indoor forced convection drying (IFCD) method may be adopted for the drying of groundnuts in which the product is dried in thin layer by continuous hot air.

Simulation models are very helpful in designing a new dryer or in improving an existing dryer for the drying of agricultural products. Many researchers have carried out the studies on the mathematical modelling and experimental studies on thin layer drying phenomenon of various commodities, as given in Table 1.

Table 1 Summary of thin layer drying of various commodities under open sun and forced drying

S. No.	Author and year	Commodity	Drying method	Suggested model
1	Akpinar et al., 2003	Red pepper slices	Convective dryer	Diffusion model
2	Toğrul and Pehlivan, 2004	Apricots, grapes, peaches, figs and plums	OSD	Diffusion model (apricot and figs), modified Henderson and Pabis model (plum) and Verma et al. model (peach).
3	Gunhan et al., 2005	Bay leaves	Laboratory dryer	Page model
4	Akpinar, 2006	Parsley, mint and basil	OSD	Modified Page model and Verma et al. model
5	Yang et al., 2007	Peanut	Trailer type dryer	Henderson-Pabis, Hummeida and Modified Oswin equilibrium moisture content (EMC) model
6	Saeed et al., 2008	Roselle	Constant temperature and humidity chamber	Two-term exponential model
7	Meisami-asl and Rafiee, 2009	Apple	Laboratory convective dryer	Midilli et al. model
8	Toğrul, 2010	Black grapes	Laboratory dryer	Page model
9	Kumar et al., 2011	Khoa	OSD and greenhouse drying	Exponential model
10	Kouchakzadeh and Haghihi, 2011	Pistachios	Laboratory scale vacuum dryer	Logarithmic model
11	Mao et al., 2012	Australian peanut	Hot air drying	Two term model
12	Darvishi, 2012	Potato slices	microwave dryer	Midilli et al. model
13	Kumar et al., 2012	Carrot pomace	laboratory scale hot air forced convection dryer	Hii et al. model
14	Kaleta et al., 2013	Apple	Fluidized bed dryer	Page model
15	Jayashree and Visvanathan, 2013	Ginger	OSD	Diffusion model
16	Mihindukulasuriya and Jayasuriya, 2013	Chilli	hot air oven and fluidized bed dryer	Midilli et al. model
17	Purkayastha et al., 2013	Tomato slices	Hot air drying	Logarithmic model
18	Bagheri et al., 2013	Tomato slices	Laboratory dryer	Page model
19	Gharehbeglou et al., 2014	Turnip	Laboratory dryer	Modified Henderson and Pabis and Hii, Law and Cloke models
20	Mutuli and Mbuge, 2015	Cowpea leaves and jute mallow	Convective laboratory dryer	Page model
21	Taghipour et al., 2016	Lime slices	Laboratory dryer	Peleg model
22	Dhanushkodi et al., 2017	Cashew	Solar biomass hybrid dryer	Page model

From the vast literature, it is observed that the information on thin layer drying behaviour of groundnut under OSD and IFCD is not available. Therefore, this study has been carried out to fulfil the existing gap on thin layer modelling of groundnut. The main objectives of this study are (i) to investigate the drying kinetics of groundnut under OSD and IFCD modes, and (ii) to study the most suitable drying model for describing the drying behaviour of groundnut under given conditions. This study would be useful to predict the drying behaviour of groundnut in OSD and IFCD modes.

2 Materials and methods

2.1 Experimental set-up and instrumentation

A rectangular wire mesh tray of size 0.15×0.25 m^2 was used to accommodate the thin layer groundnut samples. A digital electronic weighing balance (Smart: made in India, capacity: 6 kg, least count: 0.1 g) was used to measure the mass of moisture evaporated. The air velocity over the surface of groundnut was measured with an anemometer (for IFCD) (Lutron: AM-4201, least count: 0.1 m s^{-2}). The whole experimental set up for OSD mode was kept in open sun at a place with negligible wind velocity. A heat convector (Model FH-812T, Usha Shriram, made in India) was used for blowing hot air over the groundnut surface during IFCD mode. The difference of two successive readings of the weighing balance gave the water evaporated during that time interval and was used in the calculations of moisture ratio (*MR*).

2.2 Sample preparation and experimental procedure

Fresh groundnuts were purchased from the farmer and cleaned to remove immature and broken pods. Groundnut samples required for experimentation were remoistened by soaking in water for 12 hours and then conditioned in shed for one hour to remove the extra moisture. The experiments were performed during the months of February and May, 2016 in the climatic conditions of Rohtak (28^{o}54′N 76^{o}34′E), India. Groundnuts of 130 g (Sample 1) and 198 g (Sample 2) under OSD and 180 g (Sample 3) under IFCD were spread in single thin layer and the tray was kept on the electronic digital weighing balance. Observations were recorded for OSD and IFCD modes. The observation time interval for IFCD was taken as 30 minutes whereas for OSD it was an hour. The two consecutive values of weighing balance directly gave the moisture evaporated during that time interval and was used in the calculations. The groundnut samples were dried up to the safe storage moisture level of 8% to 10% (w.b.).

The experimental data obtained for the groundnut weight were used for the drying kinetics of groundnut in terms of moisture removal rate. The moisture content data for both experimental modes were converted into *MR* and were used for different drying models as defined in Table 2.

Table 2 Thin layer drying models

S. No.	Model name	Model	Reference
1	Lewis	$MR = \exp(-kt)$	Lewis (1921)
2	Page	$MR = \exp(-kt^n)$	Page (1949)
3	Modified Page	$MR = \exp[(-kt)^n]$	Yaldiz et al. (2001)
4	Henderson and Pabis	$MR = a\exp(-kt)$	Henderson and Pabis (1961)

Note: k = drying constant (1/h); t = time (hrs); a = coefficient in the drying models, and n = number of constants in drying models.

The moisture ratio of groundnut during drying was estimated by using Equation (1) (Dejchanchaiwong et al., 2016).

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

where, M_t = moisture content at ‘t’ drying time (%, dry basis); M_e = equilibrium moisture content, and M_i = initial moisture content (%, dry basis).

The coefficient of correlation (*R*), reduced chi square (χ^2), root mean square error (*RMSE*) and mean bias error (*MBE*) were considered to be the primary criterion to determine the consistency of the best thin layer drying model. These parameters can be evaluated using Equations (2) to (5) (Prakash and Tiwari, 2005; Shringi et al., 2014).

$$R = \frac{N\sum_{i=1}^{N} MR_{\exp,i}\, MR_{pre,i} - \left(\sum_{i=1}^{N} MR_{\exp,i}\right)\left(\sum_{i=1}^{N} MR_{pre,i}\right)}{\sqrt{N\sum_{i=1}^{N} MR_{\exp,i}^{\ 2} - \left(\sum_{i=1}^{N} MR_{\exp,i}\right)^2}\sqrt{N\sum_{i=1}^{N} MR_{pre,i}^{\ 2} - \left(\sum_{i=1}^{N} MR_{pre,i}\right)^2}} \quad (2)$$

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

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

$$MBE = \frac{\sum_{i=1}^{n}(MR_{\exp,i} - MR_{pre,i})}{N} \quad (5)$$

where, $MR_{\exp,i}$ is the experimentally calculated moisture ratio and $MR_{pre,i}$ is the predicted moisture ratio for the model. *N* and *n* are the number of observations and number of constants respectively. The model suitability was evaluated by considering the higher value of *R* and least values of χ^2, *RMSE* and *MBE*. The drying rate (i.e. *DR*) was expressed as the amount of moisture evaporated over time and is evaluated using Equation (6) (Meisami-asl and Rafiee, 2009):

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (6)$$

where, M_t is the moisture content at ‘t’ drying time (%, dry basis) and M_{t+dt} is the moisture content at (t+dt) drying time (%, dry basis).

3 Results and discussion

The experimental data obtained for groundnut drying under OSD and IFCD are given in Tables 3 and 4 respectively.

Table 3 Experimental data for groundnut drying under OSD

Time, *t* (hrs)	Sample 1		Sample 2	
	Wt.(g)	*MR*	*Wt*.(g)	*MR*
0	130.0	1	198.0	1
1	120.0	0.76744	182.3	0.75079
2	108.0	0.48837	164.0	0.46032
3	103.0	0.37209	157.0	0.34921
4	97.0	0.23256	148.0	0.20635
5	94.4	0.17209	144.0	0.14286
6	92.2	0.12093	141.3	0.10000
7	90.0	0.06977	139.0	0.06349
8	88.0	0.02326	137.0	0.03175
9	87.0	0	135.0	0

Table 4 Experimental data for groundnut drying under IFCD

Time, *t* (hrs)	Sample 3	
	Wt.(g)	*MR*
0	180.3	1
0.5	156.0	0.53089
1.0	144.3	0.30502
1.5	136.2	0.14865
2.0	131.7	0.06178
2.5	128.5	0

The groundnut samples were dried from initial moisture content of 38% (w.b.) to the safe storage moisture content of 8% to 10% (w.b.). Moisture ratio data of groundnut samples were fitted to four thin layer drying models and the statistical parameters such as R, χ^2, *RMSE* and *MBE* along with their constants are summarized in Tables 5 and 6 respectively.

Table 5 Modeling of *MR* for thin layer drying of groundnut under OSD

Sample no.	Model name	*k*	*n*	*a*	*R*	*RMSE*	χ^2	*MBE*
Sample 1	Lewis	0.254911			0.99667	0.09402	0.00994	0.08328
	Page	0.063051	0.3170		0.96067	0.62474	0.50182	0.55646
	Modified Page	0.214199	0.1049		0.79433	0.21653	0.06028	0.08474
	Henderson and Pabis	0.43002		1.21546	**0.99238**	**0.07555**	**0.00734**	**0.01763**
Sample 2	Lewis	0.266072			0.99487	0.09839	0.01089	0.08726
	Page	0.050828	0.3008		0.96029	0.65741	0.55566	0.58911
	Modified Page	0.504912	0.0654		0.77821	0.21855	0.06141	0.07942
	Henderson and Pabis	0.419298		1.1109	**0.99588**	**0.04007**	**0.00206**	**0.00715**

Table 6 Modeling of *MR* for thin layer drying of groundnut under IFCD condition

Sample no.	Model Name	*k*	*n*	*a*	*R*	*RMSE*	χ^2	*MBE*
Sample 3	Lewis	0.77547			0.99759	0.09665	0.01168	0.08640
	Page	0.44056	0.24973		0.98163	0.56470	0.53147	0.49330
	Modified Page	0.31849	1.91987		0.86050	0.50995	0.43341	0.45221
	Henderson and Pabis	1.36829		1.06832	**0.99842**	**0.03468**	**0.00200**	**0.00787**

The variation of moisture ratio with respect to drying time for the drying of groundnut samples 1, 2 (OSD) and 3 (IFCD) are shown in Figures 1, 2 and 3 respectively.

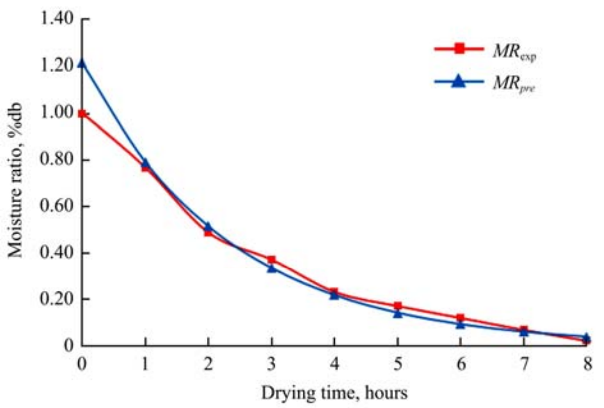

Figure 1 Variation of moisture ratio with respect to drying time for the drying of groundnut sample 1 under OSD mode

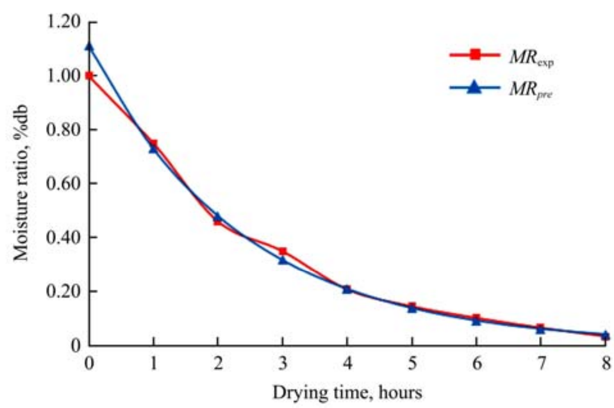

Figure 2 Variation of moisture ratio with respect to drying time for the drying of groundnut sample 2 under OSD mode

Similarly, the variation of drying rate with respect to drying time for the drying of groundnut samples under OSD and IFCD are shown in Figures 4 and 5 respectively.

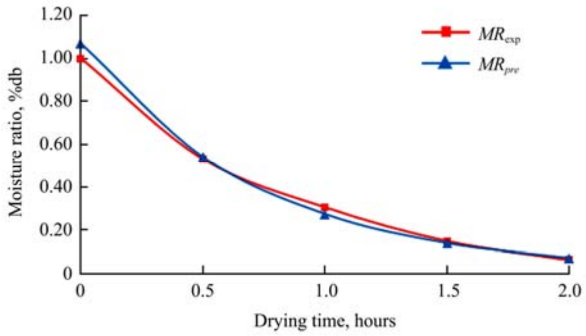

Figure 3 Variation of moisture ratio with respect to drying time for the drying of groundnut sample 3 under IFCD mode

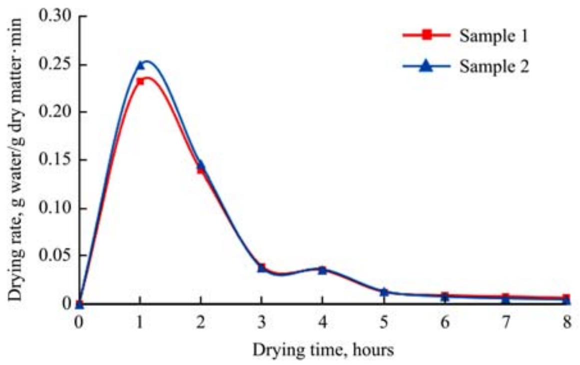

Figure 4 Variation of drying rate with respect to drying time for the drying of groundnut under OSD mode

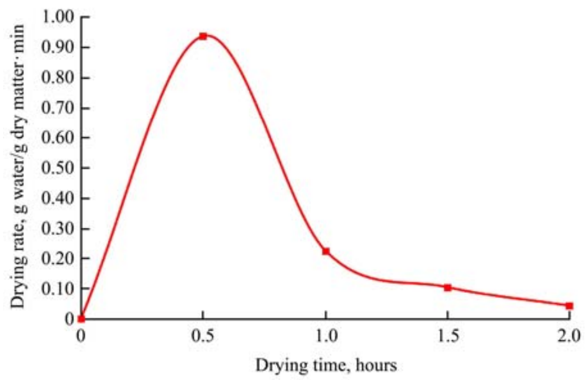

Figure 5 Variation of drying rate with respect to drying time for the drying of groundnut under IFCD mode

From the Tables 5 and 6, it is observed that Henderson and Pabis model with highest value of *R* (0.99588 and 0.99842) and lowest values of χ^2 (0.00206 and 0.00200), *RMSE* (0.04007 and 0.03468) and *MBE* (0.00715 and 0.00787) was found to be most suitable for groundnut drying under both, i.e., OSD and IFCD modes among all the models investigated. Yang et al. (2007) has also suggested the Henderson and Pabis model for drying groundnuts inside a trailer type dryer. From Tables 5 and 6, it is also observed that the values of statistical parameters under Lewis model are also very close to the values under Henderson and Pabis model. Groundnut drying under both modes occurred in the falling rate drying period from initial to final moisture content. From Table 5, it can be seen that the value of drying constant ‘*k*’ during drying of groundnuts under OSD mode for Lewis model is observed to be 0.254911 and 0.266072 and for Henderson and Pabis model it is found to be 0.43002 and 0.419298 for sample 1 and sample 2 respectively. From Table 6, it can be seen that the value of drying constant ‘*k*’ for drying of groundnuts under IFCD condition for Lewis model is found to be 0.77547 and for Henderson and Pabis model it is found to be 1.36829. It is pertinent to mention here that the air temperature for IFCD condition was higher than the OSD condition throughout the experiment. Thus, it can be concluded that the value of drying rate constant increases with the increase in drying air temperature. Similar results have also been reported in the literature for drying apricots, grapes, peaches, figs and plums (Toğrul and Pehlivan, 2004), red pepper slices (Akpinar, 2006), apple (Meisami-asl and Rafiee, 2009), pistachios (Kouchakzadeh and Haghihi, 2011), and tomato slices (Bagheri et al., 2013). From Figures 4 and 5, it is observed that the drying rate is higher in case of IFCD condition. This means that the time required to dry the groundnut up to the safe storage moisture content forced convection mode is shorter.

4 Conclusion

The thin layer drying behaviour of the groundnuts were studied under OSD and IFCD modes. The groundnuts were dried from initial moisture content of 38% (w.b.) to the safe storage moisture content of 8%-10% (w.b.). The entire drying process was observed to occur in falling rate period. Four thin layer drying models were used in order to illustrate the best drying model for groundnut drying under OSD and IFCD modes. Among these Henderson and Pabis model with highest value of *R* (i.e. 0.99588 and 0.99842), and lowest values of χ^2 (i.e. 0.00206 and 0.00200), *RMSE* (i.e. 0.04007 and 0.03468) and *MBE* (i.e. 0.00715 and 0.00787) under OSD and IFCD respectively was observed to be most suitable for describing the drying behaviour of groundnut. The values of *R*, χ^2, *RMSE* and *MBE* under Lewis model were also observed to be very close to Henderson and Pabis model. Drying rate during IFCD mode was found to be higher than OSD. Therefore, it is concluded that the Henderson and Pabis and Lewis models are the most suitable for describing the drying behaviour of groundnut sample in OSD and IFCD modes.

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Nomenclature

a	Coefficient in the drying models
k	Drying constants (1/h)
DR	Drying rate (g water/g dry matter·min)
$MR_{\exp,i}$	Moisture ratio
$MR_{pre,i}$	Experimental moisture ratio
M_e	Predicted moisture ratio
M_i	Equilibrium moisture content
M_t	Initial moisture content (%, dry basis)
M_{t+dt}	Moisture content at ‘t’ drying time (%, dry basis)
MBE	Moisture content at (t+dt) drying time (%, dry basis)
MBE	Mean bias error
N	Number of observations
n	Number of constants in drying models
$RMSE$	Root mean square error
R	Coefficient of correlation