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MODELLING THE DRYING KINETICS OF RED CHILIES AS A FUNCTION OF LAYER THICKNESS

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ABSTRACT

Modelling the drying kinetics of red chilies (Capsicum annuum L) were studied as thin layer with sample thicknesses of 1, 2 and 3 cm in a natural convective solar dryer. Red chilies were dried from an initial moisture content of about 81.23% (w.b) to a moisture content of 7.13% (w.b). The drying data were fitted with two thin layer drying models namely Page model and Henderson-Pabis model. The values of the empirical parameters for the models were determined by the regression equation of the best fitted line. The fit of goodness of the models were evaluated by using correlation coefficient (r), Chi-square (χ^2) and Root Mean Square Error (RMSE). Both models satisfactorily described the drying curve of chilies at 1cm layer thickness. In comparing the experimental moisture values with those model predicted values, it was shown that the Henderson-Pabis model displayed the best fit quality with correlation coefficient of 0.85, χ^2 of 0.0213 and RMSE of 0.128 concluding that Henderson-Pabis model is optimal for simulating drying kinetics of red chilies at 1cm layer thickness.

KEYWORDS: Chi-square, Convective solar dryer, Henderson-Pabis model, Page model, Root Mean Square Error.

INTRODUCTION

Chilli is one of the important spices in Sri Lankan meals. It is mainly grown for dry chilli production with an annual production of 7,500 Mt (Central Bank Report, 2002). However, it is harvested as green pods as well. The red chilies contain a moisture content in the range of

300%-400% (db) at the time of harvest which is prone to pest attack during storage (Chand and Singh, 2007). Thus, reducing the moisture content to 8-9% (db) is recommended for ideal processing and storage conditions which is achieved by means of drying (Chand and Singh, 2007).

Drying is a complex thermo-physical and biochemical process with simultaneous heat and mass transfer between the surface of the material and the surrounding media (Hossain and Bala 2002). Modelling drying kinetics has proved to be an important tool used to analyze these transfer processes of agricultural products during drying. Thin-layer drying equations are often used to describe the drying kinetics of various types of agricultural produces. Thus, numerous mathematical models for the thin layer drying of many agricultural products have been proposed.

These models fall mainly into three categories, namely, theoretical, semi-theoretical and empirical. However, the empirical equations are easily applied to drying simulation as they depend on experimental data. The empirical models derive a direct relationship between the average moisture content and drying time (Keey,1972). The present study was therefore, undertaken to model the thin layer drying characteristics of red chilies with different layer thicknesses in a natural convective solar dryer. The objective of this study was to model the drying kinetics of red chilies using two thin layer drying models namely '*Page*' and '*Henderson and Pabis*' model.

MATERIALS AND METHODS

Sample preparation

Freshly harvested red chilli samples were cleaned and stored in a refrigerator at 4^0C until the drying experiments. Before the experiments, the samples were removed from the refrigerator and their temperature were allowed to become equilibrium with that of atmospheric temperature (27± 1°C).

Drying experiment

Drying treatments were performed in a natural convection solar dryer between 8.00 a.m - 4.00 p.m on bright sunny days. Approximately 1kg of chili samples with initial moisture content of 90.3% were uniformly spread on stainless steel rays and kept inside the dryer. Drying was carried out at 1cm, 2cm and 3cm layer thicknesses in separate trays. The drying runs were continued until an equilibrium moisture content of 7.13% (wb) was obtained. The weights of the samples were taken using an electronic balance at 3-hour interval until the weight was constant (samples attained equilibrium moisture content with the drying air conditions). The weight of the samples was taken quickly to avoid interference with the drying process. It was assumed that both moisture content and temperature of samples were uniform throughout the layers at any given time during the drying process. Around 5g of sample from each replication were taken to find out the moisture content. The final moisture content of the samples was determined by the oven drying method and the value obtained was taken as the equilibrium moisture content of the sample (at the drying air conditions). Each drying layer thicknesses were replicated thrice and the mean values were used for data analysis.

Thin layer drying models

Two thin layer drying models were used to describe the drying characteristics of chilies and to determine the model parameters by fitting experimental data. The thin layer drying models used in this study are given in Table 1.

Table 1: Thin layer drying models applied to the drying of red chilies.

No	Model Name	Model Equation	Reference
1.	Page	$MR = exp\ (-kt^n)$	Page, 1949
2.	Henderson and Pabis	$MR = a\ exp\ (-kt)$	Henderson and Pabis, 1961

Evaluation of models

Based on the initial moisture content from oven drying, the weight loss was measured in order to calculate the moisture ratio. The moisture ratio of chillies at a given time, *t* was calculated as reported by Goyal *et al.* (2006) and Akoy (2014). The drying curve for each experiment was obtained by plotting the dimensionless moisture ratio of the sample vs. the drying time.

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad \ldots\ldots\ldots\ldots Equation\ 1$$

Where,

MR is moisture ratio

M_i and M_e are the initial and equilibrium dry basis moisture contents, %

M_t is dry basis moisture content at any time ‘t’

Determination of drying constants

The two thin-layer drying models were transformed for the determination of the constants as follows:

1. Page Model

$MR = exp\ (-kt^{n})$ ....$Equation\ 2$

$\ln MR = -kt^{n} - \ln(MR) = kt^{n}$

$\ln\,(-ln(MR)) = \ln k + n\ lnt$

$MR = \ln k + n.\ lnt$ ....Equation 3

Equation 3 is in the form of a straight line. The relationship is as follows:

$y = MR$

$m = n$

$x = \ln t$

$c = \ln k$

Where, MR is the moisture ratio, '*t*' is time (hour), and 'k' (h^{-1}) and '*n*' are empirical parameters of the model.

2. Henderson - Pabis Model

$MR = a.\exp\,(-\mathrm{k}t)$.. .... Equation 4

$\ln MR = \ln a - kt$

$\ln MR = -kt + \ln a$ ....Equation 5

$y = -m.\ x + C$

The equation above is also in the form of a straight line and they relate as follows:

$y = \ln MR$

$m = -k$

$x = t$ and

$c = \ln a$

Where,

MR is the moisture ratio, '*t*' is time (hour), and '*a*', '*k*' and '*n*' are empirical parameters of the model.

The experimental data were fitted in the straight line form of *Page* model and *Henderson-Pabis* model against changes in moisture ratio versus natural log of drying time. The model empirical parameters (drying constants) were determined by the regression equation of the best fitted line.

Fitness of the models

Page model and *Henderson & Pabis* model were fitted with the drying data to predict the moisture ratio (MR). The correlation coefficient (*r*) was used as primary criteria for selecting the model that best fit the experimental data. In addition to this, the models were also evaluated based on the Chi-square (χ^2) and the Root Mean Square Error (RMSE). The lower chi- square ($\chi2$) and RMSE values and the higher correlation coefficient values were chosen as the basis for goodness of fit (Akpinar *et al.*, 2006; Akpinar et al., 2003a, b, c; Günhan et al., 2005; Midilli and Kucuk, 2003).

$$r = \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,avg}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{exp,avg}\right)^2} \ldots\ldots\ldots\ldots\ldots\ldots \mathit{Equation\ 6}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 7}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \ldots\ldots\ldots\ldots \mathit{Equation\ 8}$$

Where,

MRexp,i - *i*th experimentally observed moisture ratio,

MRpre,i - *i*th predicted moisture ratio,

MRpre, avg - average experimental moisture ratio,

N - Number of observations

n - Number constants.

RESULTS AND DISCUSSION

Determination of empirical parameters of the models

The estimated empirical parameters of the two models for all the three drying layer thicknesses are presented in Table 2. The estimated value of the drying rate constant (*k*) decreased with the increase in layer thickness in both models. This implies that with increase in layer thickness, drying curve becomes less steep indicating decrease in drying rate.

Table 2: Empirical parameters of the fitted drying models.

Layer thickness	*Page 'n'*	*Page ' k'*	*Henderson-Pabis 'a'*	*Henderson-Pabis 'k'*
1 cm	-0.2736	8.3178	1.2248	-0.0531
2 cm	-0.1664	7.1771	1.1768	-0.0183
3 cm	-0.1095	5.2941	1.0731	-0.0069

Fitting the thin layer drying models to the drying curves

The accuracy of both models were evaluated by comparing the predicted moisture ratios with the observed values as shown in Figures 1-6 for varied thicknesses. For each investigated layer thickness, the experimental drying data were fitted in the Henderson–Pabis model and Page model. Figures 1-6 present the variation of moisture ratio as a function of drying layer thickness. It was observed that when moisture ratio decreased with time, the difference between moisture ratios increased gradually from beginning to end of drying. Both models provided a good conformity between the experimental data and the predicted moisture ratios of different layers of chilies dried in the natural convective solar dryer.

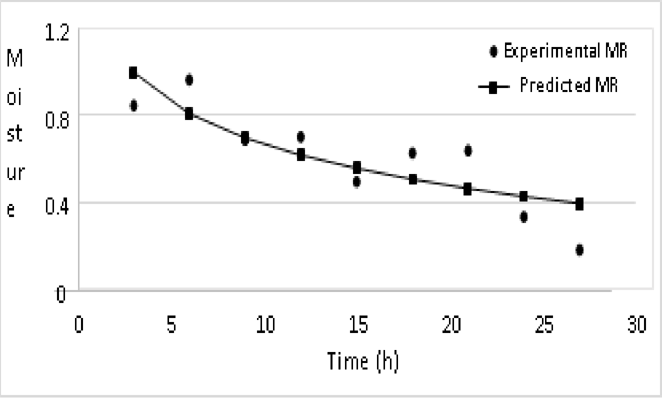

Figure 1: Comparison of experimental and predicted moisture ratio values by *Page* model at 1cm layer thickness.

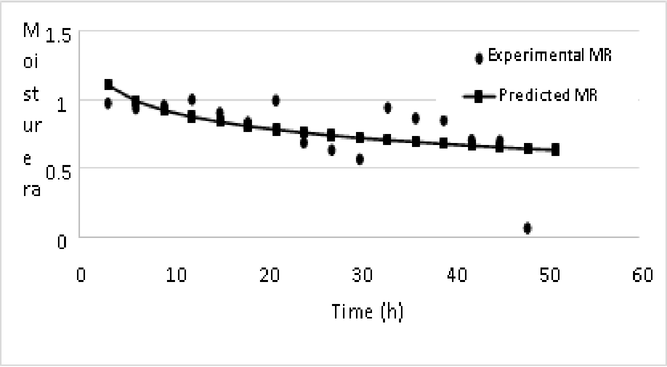

Figure 2: Comparison of experimental and predicted moisture ratio values by *Page* model at 2cm layer thickness.

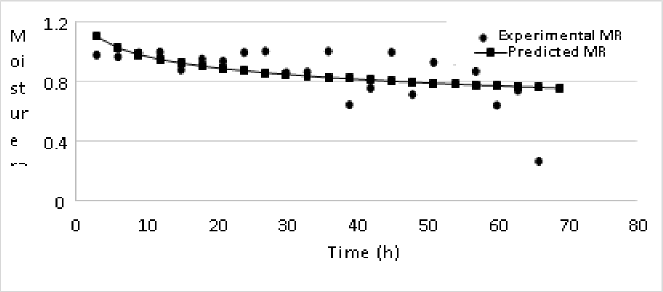

Figure 3: Comparison of experimental and predicted moisture ratio values by *Page* model at 3cm layer thickness.

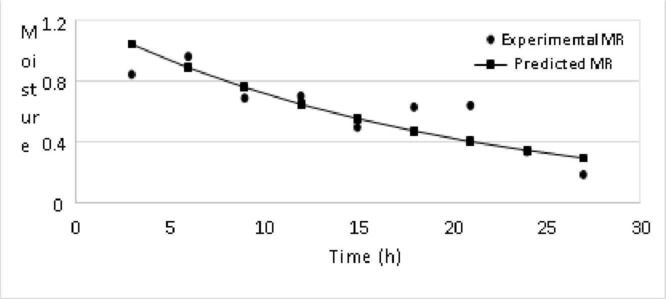

Figure 4: Comparison of experimental and predicted moisture ratio values by *Henderson-Pabis* model at 1cm layer thickness.

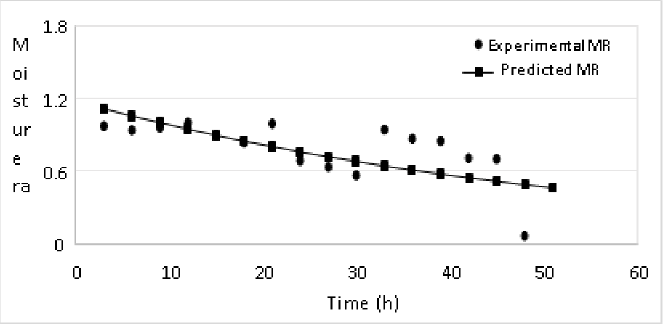

Figure 5: Comparison of experimental and predicted moisture ratio values by *Henderson-Pabis* model at 2cm layer thickness.

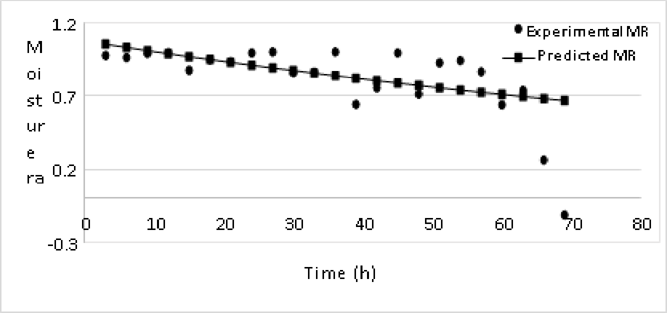

Figure 6: Comparison of experimental and predicted moisture ratio values by *Henderson-Pabis* model at 3cm layer thickness.

Goodness of the fit of models

The accuracy of both models was evaluated by comparing the predicted moisture ratios with the observed values. The summary of statistical evaluation of both models using three different criteria are presented in the Tables 3 as per the procedure described by Akpinar *et al*. (2006).

Table 3: Statistical tests on both models for each layer thickness

Drying model	**Layer thickness of chilies**	χ^2	**r**	**RMSE**
Page	1cm	0.022	0.81	0.132
	2cm	1.178	0.38	1.019
	3cm	0.059	0.5	0.232
Henderson and Pabis	1cm	0.021	0.84	0.128
	2cm	1.084	0.43	0.978
	3cm	0.048	0.48	0.211

χ^2 = Chi square, r = Correlation coefficient, RMSE = Root-Mean-Square Error

Henderson & Pabis model displayed correlation coefficient (*r)* range from 0.43 to 0.85 and RMSE varied from 0.128 to 0.978 cross the three drying layers of chilies. It also produced Chi-square (χ^2) values from 0.0213 to 1.084. However, *r* values varied from 0.38 to 0.81 and the χ^2 varied from 0.022 - 1.178 and RMSE varied from 0.132 - 1.019 for *Page* model across the three drying layers of chilies.

Both Page model and Henderson-Pabis model gave consistently high correlation coefficient values of 0.81 and 0.85 respectively at 1cm layer thickness, indicating that both models can satisfactorily describe the drying behavior of chilies with layer thickness of 1cm. Both models did not display acceptable correlation coefficient and RMSE at 2cm and 3cm layer thicknesses. Therefore, both models show best fit only with the layer thickness of 1cm. This could be because that both models being empirical, they are capable of describing thin layer water removal and the heat penetration during drying (Da Silva *et al*., 2014). As a consequence, the model fitness was found to be poor at 2cm and 3cm layer thicknesses.

However, studies show that *Page* model was also reported to fit the thin layer drying data better than other models in many earlier studies such as Akpinar *et al*. (2006) for aromatic plants, Doymaz (2004) for carrots and Hossain and Bala (2002) for green chillies. The *Page* model has been reported to exhibit a better fit than other models in accurately simulating the drying curves of chili (Tunde-Akintunde, 2011), (Doymaz and Pala, 2002) rape seed (Han *et al.*, 2011.), okra, (Simal *et al.*, 2005) and kiwi. *Henderson & Pabis* model was also successfully used by (Doymaz, 2004; Sacilik *et al*., 2006) for the prediction of drying time and for generalization of drying curves. However, in this present study it was observed that *Henderson - Pabis* model produced the highest *r* values and the lowest χ^2, RMSE values than *Page* model at all the three layer thicknesses evaluated.

Drying of materials having high moisture content is a complicated process involving simultaneous heat and mass transfer (Yilbas *et al*., 2003). Therefore, the thin-layer drying models used in this study describe the process of drying in a single layer of chilies. Because layer thicknesses maintain its moisture because of low air movement within masses of chillies that may require longer time to dry. As drying depth increased, there was a linear increase in drying time and vice versa. As these models consider only the external resistance to moisture transfer between product and drying air (Midilli *et al*., 2002, Panchariya *et al*., 2002) they neglect the fundamentals of drying process and presents a direct relationship between average moisture and drying (Ozdemir and Devres 1999, Wang and Singh 1978). Hence, the goodness of the fit of these models at 2cm and 3cm of drying layer thickness were found to be unsatisfactory.

Both models exhibited *r* values more than 0.8 at 1cm layer thickness, suggesting that the selected models gave excellent fit to the experimental data Though, both models were comparable with each other in terms of modeling accuracy (Table 3), *Henderson-Pabis* model may be assumed to represent the thin layer drying of red chilies better in a natural convective solar dryer.

CONCLUSIONS

Model fitting procedure shows that both *Page* model and *Henderson-Pabis* model showed the best curve fitting for the experimental moisture ratio value for the chillies with 1cm layer thickness in a natural convective solar dryer. Both models did not show better fit with 2 cm and 3 cm layer thicknesses. *Henderson & Pabis* model was found to be better than *Page* model due to its highest *r* (0.85) and lower values of χ^2 (0.0213) and RMSE (0.128). Therefore, it can be concluded that *Henderson-Pabis* model better described the drying curves of chili in natural convective solar-dryer with 1cm layer thickness.

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