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MODELLING OF THIN LAYER DRYING KINETICS OF COCOA BEANS DURING ARTIFICIAL AND NATURAL DRYING

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Abstract

Drying experiments were conducted using air-ventilated oven and sun dryer to simulate the artificial and natural drying processes of cocoa beans. The drying data were fitted with several published thin layer drying models. A new model was introduced which is a combination of the Page and two-term drying model. Selection of the best model was investigated by comparing the determination of coefficient (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) between the experimental and predicted values. The results showed that the new model was found best described the artificial and natural drying kinetics of cocoa under the conditions tested.

Keywords: Cocoa, Artificial Drying, Sun Drying, Modelling, Regression.

1. Introduction

Currently, cocoa (*Theobroma Cacao* L.) planted in Malaysia, as according to the forecasted statistic, has planting areas of 30,000 ha with the smallholders dominating about 77% of the nation planting areas [1]. Sabah still remains the main producer for cocoa while in the Peninsular regions the main producing states are Pahang and Perak.

Upon harvesting of ripe cocoa pods, fresh cocoa beans are fermented in wooden boxes for 5-7 days and dried until it reaches the safe moisture level of 7.5% (wet basis). Drying techniques vary among the farmers and it ranges from

Nomenclatures

a, b, c	Drying coefficients (equations Table 1)
k, g, n	Drying constants (equations Table 1)
MR	Moisture ratio (dimensionless)
N	Number of observations
R^2	Determination of coefficient
RMSE	Root mean square error
RH	Relative humidity (%)
z	Number of coefficients & constants

Greek Symbols

χ^2	Reduced chi-square

Subscripts

i	At time i
e	Equilibrium
o	Initial
exp	Experimental
pre	Predicted

the natural sun drying technique to the artificial hot air technique. The selection of drying technique largely depends on the production scale and affordability in terms of cost. Currently, sun drying is still the most widely used method especially by cocoa smallholders due to its simplicity, low cost set up and requires only direct sunlight which is renewable and abundant. It was also reported that sun dried cocoa beans have better flavour quality and less acidic due to its gentle drying process [2]. On the other hand, artificial hot air drying method is normally associated with beans of weaker flavour quality, higher acidity, insufficient browning, smoke contamination and case hardening [3].

Mathematical modelling of the cocoa drying process has been reported in literatures mostly in hot air drying under continuous operation [4-7]. However, there is no report at all on modelling of the thin layer drying kinetics of cocoa beans using natural and artificial drying processes that simulates the real farm operation. New semi-theoretical models were also proposed to better suit the drying kinetics. Therefore, the present study was carried out to model the thin layer drying kinetics of cocoa beans in natural and artificial drying and select the best model for these processes.

2. Materials and Methods

2.1 Sample preparation

Fresh cocoa beans were obtained from Jengka, Pahang and fermented using wooden boxes for five days. The beans were turned every 48 hours to ensure uniformity during fermentation. Upon fermentation, the beans were spread on a sun dryer with meshed drying platform. In order to simulate the actual practices of artificial drying, the fermented beans were dried using an air-ventilated oven at air temperature of 60°C, which is recommended for cocoa. Temperature higher than 60°C has been reported to give deteriorating effect on cocoa quality [3].

2.2 Drying procedure

Drying commenced from 8 a.m. till 6 p.m daily and was terminated when the beans moisture content reached 7.5% (wet basis). This is the safe moisture content as indicated in the Malaysian Dried Cocoa Standard [8]. In order to simulate the actual on farm operation, in artificial drying using oven, the beans were let tempered at room temperature overnight. The purpose of this step is for the moisture within the beans to redistribute from the internal to the outer layer of the beans (testa) because the testa will generally dry faster than the cotyledon layer in hot air drying. Moisture content of the beans in both techniques was taken every 2 hours using a moisture balance (AND Instrument, USA) with 5 g ground sample heated at 105°C.

2.3 Temperature measurement

The ambient temperature and humidity were measured using a data logger (Rotronic HW3, Germany) for the sun drying. The oven temperature was recorded, which was found constant most of the times with variation of only ±1 °C. The relative humidity in the oven was estimated at 6% since it was ventilated and assumed no accumulation of excess moisture in the oven.

2.4 Mathematical modelling

The thin layer drying models listed in Table 1 were used. These are semi-theoretical and empirical models used in literatures. Semi-theoretical models are derived based on theoretical model (Fick's second law) but are simplified and added with empirical coefficients in some cases to improve curve fitting. In the empirical models a direct relationship is derived between moisture content and drying time and the parameters associated with it have no physical meaning at all.

A new model was developed which is a combination of the Page equation and the Two-term model. The page equation was found in several literatures to be able to fit drying curves of various food products [17] while the two-term model is basically derived from the first two terms of the Fick's law analytical solution. By combining the advantages of these two factors is believed that this new model can be used for modelling.

In these models, the moisture ratio (MR) is defined as $(M_i-M_e)/(M_o-M_e)$ where the subscripts i, e and o denote at time i, equilibrium and initial, respectively. Non-linear regression was performed using the least square method. Statistical parameters such as the coefficient of determination (R^2), reduced chi-square (Equation 11) and root mean square error (Equation 12) were used as the criteria for selecting the best model.

Table 1. Thin Layer Drying Models Tested for Cocoa Drying.

Model name	Model equation	Equation No.	References
Newton	$MR = exp^{(-kt)}$	1	[9]
Henderson and Pabis	$MR = a\,exp^{(-kt)}$	2	[10]
Page	$MR = exp^{(-kt^n)}$	3	[11]
Logarithmic	$MR = a\,exp^{(-kt)} + c$	4	[12]
Two term model	$MR = a\,exp^{(-kt)} + c\,exp^{(-gt)}$	5	[13]
Verma et al.	$MR = a\,exp^{(-kt)} + (1-a)\,exp^{(-gt)}$	6	[14]
Diffusion approach	$MR = a\,exp^{(-kt)} + (1-a)\,exp^{(-kgt)}$	7	[10]
Midili-Kucuk	$MR = a\,exp^{(-kt^n)} + bt$	8	[15]
Wang and Smith	$MR = 1 + at + bt^2$	9	[16]
New model	$MR = a\exp^{(-kt^n)} + c\exp^{(-gt^n)}$	10	This paper

Chi-square: $$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N-z} \quad (11)$$

Root mean square error: $$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{1/2} \quad (12)$$

Where, N = no. of observations, z = no. of constants, $MR_{exp,i}$ = i^{th} experimental data, $MR_{pre,i}$ = i^{th} predicted data. In general, the higher the R^2 values and the lower the χ^2 and RMSE values indicate that the model is best fitted. Non-linear Regression analysis was performed using Microsoft Excel Solver (Microsoft Office, USA).

3. Results and Discussion

3.1 Drying curves

Figure 1 shows the drying curves of the artificial and natural drying processes. It is apparent that the moisture content decreased steadily with drying time. The initial moisture content was about 51% (wet basis) and during night time moisture lost was registered at about 1-5% in both techniques and this could be due to the residual heat in the beans when the heated air/sunlight no longer available.

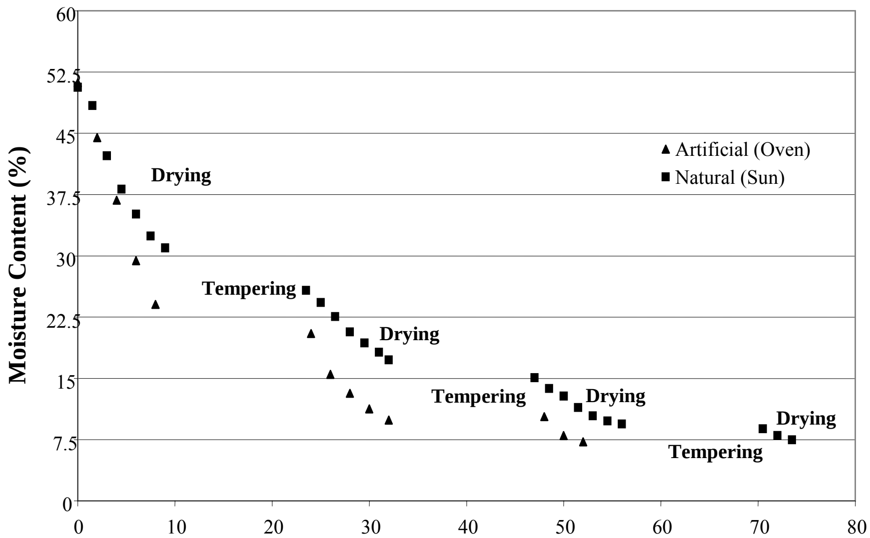

Fig. 1. Drying Curves of Artificial & Natural Drying of Cocoa Beans.

The artificial technique ended drying in 52 hours due to the faster drying rate while the natural technique ended drying in 73.5 hours. A typical temperature and humidity profile on a typical drying day is as shown in Figure 2. Ambient temperatures were found fluctuating between 26°C and 33°C while the relative humidity fluctuated between 56% and 82%. The temperatures recorded were all well below 60°C which is detrimental to quality [3].

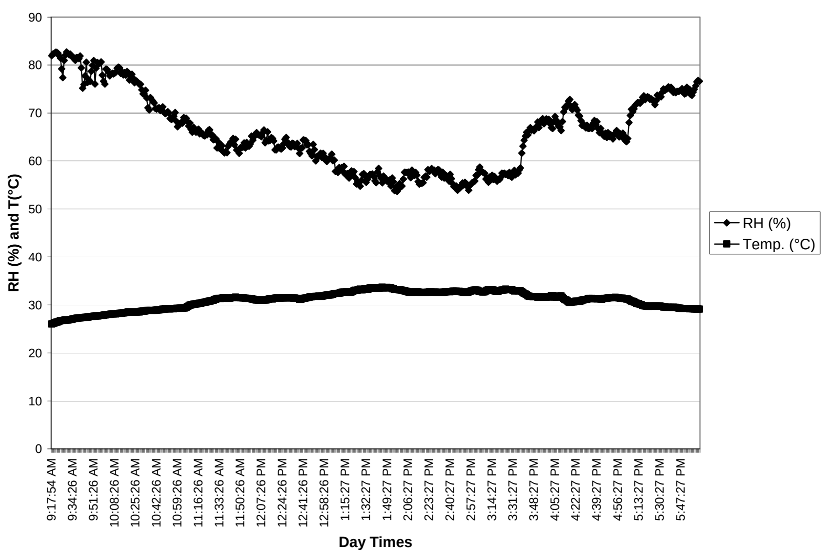

Fig. 2. Temperature & Humidity Profiles on a Typical Drying Day.

3.2 Mathematical modelling

Table 2 and 3 show the results of the regression analyses performed on the experimental data. In all cases (from Table 2 and 3), the statistical parameter estimations showed that R^2, χ^2 and RMSE values ranged from, 0.9198 to 0.9937, 0.000699 to 0.014618 and 0.02354 to 0.111215, respectively. The model that best described the thin layer drying characteristic is the one that gives the highest R^2, the lowest χ^2 and RMSE values. Based on these criteria, the new model (Equation 10) was found best described both of the drying curves with R^2, χ^2 and RMSE values of 0.9843, 0.002421, 0.038595 for the artificial technique and 0.9937, 0.000699, 0.02354 for the natural technique, respectively.

The second best fitted models were found to be the Two-term model and the Midili-Kucuk model for the artificial and natural drying techniques, respectively. Doymaz [18] reported that the Verma et al. model was found successfully applied to sun drying of figs. The Verma et al. model is another form of the Two-term model and this showed the suitability of this type of equation (two-term type) for the drying kinetics of sun drying. This is quite similar to the new model (Equation 10) used in this study.

Table 2. Results of Non-Linear Regression Analyses for Artificial Drying Curve Fitting.

Model name	Constants and Coefficients	R^2	χ^2	RMSE
Newton	k = 0.074258	0.9556	0.006553	0.077776
Henderson & Pabis	a = 0.914827 k = 0.064502	0.9499	0.005871	0.070483
Page	k = 0.150372 n = 0.738685	0.9700	0.003375	0.05344
Logarithmic	a = 0.886781, k = 0.105536 c = 0.10016	0.9622	0.00466	0.059874
Two term model	a = 0.475756, k = 0.234005 g = 0.550205, c = 0.040694	0.9759	0.003309	0.047865
Verma et al.	a = 0.449003, k = 0.040821 g = 0.221285	0.9756	0.003058	0.048501
Diffusion approach	a = 0.449003, k = 0.22129 g = 0.184474	0.9756	0.003058	0.048501
Midili-Kucuk	a = 1.02006, k = 0.161531, n = 0.718912, b = -5.5×10^{-5}	0.9702	0.004076	0.053119
Wang and Smith	a = -0.04722, b = 0.000577	0.9198	0.014618	0.111215
New model	**a = 0.563857,k = 0.073322 c = 0.430438, g = 0.002507 n = 1.73439**	**0.9843**	**0.002421**	**0.038595**

Table 3. Results of Non-Linear Regression Analyses for Natural Drying Curve Fitting.

Model name	Constants and Coefficients	R^2	χ^2	RMSE
Newton	k = 0.046244	0.9687	0.003726	0.059759
Henderson & Pabis	a = 0.92004, k = 0.042009	0.9706	0.00284	0.051019
Page	k = 0.086969, n = 0.081023	0.9754	0.002424	0.04714
Logarithmic	a = 0.944955, k = 0.03787 c = -0.03541	0.9713	0.002891	0.050298
Two term model	a = 0.536792, k = 0.047428 g = 0.036084, c = 0.385463	0.9707	0.003122	0.051003
Verma et al.	a = 0.814452, k = 0.037452 g = 0.356637	0.9818	0.001953	0.04134
Diffusion approach	a = 0.186561, k = 0.351508 g = 0.106272	0.9819	0.001953	0.041343
Midili-Kucuk	a = 1.023606, k = 0.127959 n = 0.629975, b = -0.00196	0.9845	0.0017	0.037639
Wang and Smith	a = -0.03169, b = 0.000259	0.9563	0.077596	0.084339
New model	**a = 0.405709,k = 0.078996 c = 0.596881, g = 0.00152 n = 1.80342**	**0.9937**	**0.000699**	**0.02354**

However, for the artificial drying technique (oven drying with overnight tempering) no similar studies could be found from literature. In general, various models can be fitted depending on the nature of the drying kinetics and the drying conditions used as reported in various published literatures [17-20]

Figures 2 and 3 show the comparison of the predicted and experimental values for the artificial and natural drying techniques, respectively. The prediction using the new model showed MR values banded along the straight line. The natural drying technique showed better fitting as compared to the artificial technique and this can seen be from the higher R^2 value obtained for the natural drying method. Nevertheless, the assumed model was found able to describe the drying kinetics of cocoa beans in both techniques.

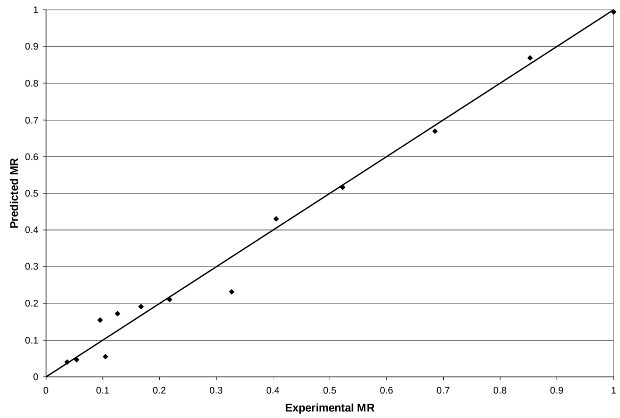

Fig. 2 Comparison of Experimental Moisture Ratio with Predicted Moisture Ratio for Artificial Drying using the New Model (R^2, χ^2 and RMSE Values of 0.9843, 0.002421 and 0.038595).

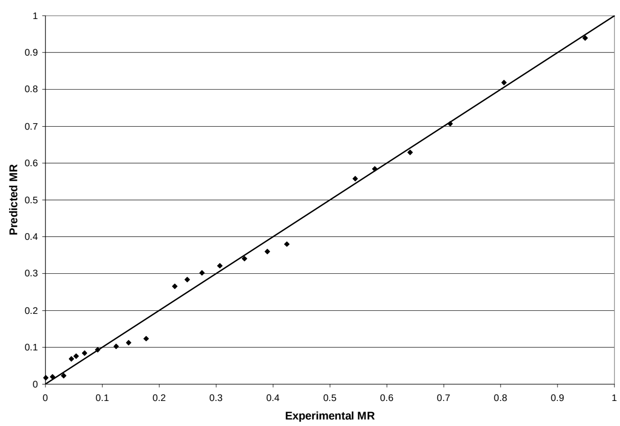

Fig. 3 Comparison of Experimental Moisture Ratio with Predicted Moisture Ratio for Natural Drying Using the New model (R^2, χ^2 and RMSE Values of 0.9937, 0.000699 and 0.02354).

4. Conclusions

Regression analyses were carried out to select the thin layer model that best described the drying kinetics of the artificial and natural drying of cocoa beans. Results showed that the new model proposed in this study was able to describe the drying kinetics of both techniques with R^2, χ^2 and RMSE values of 0.9843, 0.002421, 0.038595 for the artificial technique and 0.9937, 0.000699, 0.02354 for the natural technique, respectively. This model is a combination of the page and two-term drying models.

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