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Drying kinetics of custard apple pulp in natural circulation solar dryer

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Abstract
Custard apple (*Annona squamosa*) is popularly called as sitaphal belonging to Annonaceae family. In the investigation custard apple pulp was dried in natural circulation solar dryer and evaluated drying characteristics of custard apple pulp viz., drying rates, moisture diffusivity. The drying data of custard apple pulp was used to calculate the effective diffusion coefficients by the equation of Fick's law of diffusion. Also it was fitted to study the various models. The moisture diffusivity of custard apple pulp was found 9.12816 x 10^{-7} m²/s. Among the all four models studied, the logarithmic model was found most satisfactory to represent the drying of custard apple pulp.

Keywords: custard apple powder, custard apple pulp, solar drying, drying characteristics, modeling

Introduction
Custard apple is considered as one of the delicious and nutritionally valuable fruit, contains about 28-55% of edible portion consisting of 67% moisture, 1.60% protein, 0.30% fat, 0.70% mineral matter, 23.90% carbohydrates, 0.20% calcium, 0.40% phosphorus, 1.0% iron, 12.4-18.15% sugar, 0.26-0.65% acidity and with caloric value of 105KCal/100g. It is generally classified as semi wild fruit by virtue of its spontaneous spread in forests, wastelands and other uncultivated places. Custard apple ripens within four days after harvest. Fruits can safely be ripened in straw and fruit leaves and stored at room temperature with a shelf life of four days. The ripe fruits being soft require careful handling in marketing (Gamboa *et al*., 2005) [6]. Like many other tropical fruits, the mature custard apple fruits get chilling injury if stored below 15°C, while ripe fruits can be stored at 5°C, for six weeks. It is a tropical fruit which shows very short storage life at room temperature due to its fast ripening. Drying is useful means to increase the shelf life and reduce water activity of perishable food for further use (Roberts *et al.* 2008). During drying, the moisture content can be reduced up to a level ranging from 5 to 10%, which avoids microbial spoilage and undesirable enzymatic reactions (Sangamithra *et al.* 2015) [12] along with reduction in weight, volume, packaging, storage and transportation cost (Fumagalli and Silverira, 2005) [5].

Materials and Methods
Custard apple pulp was taken from Horticulture Department, Rajasthan College Of Agriculture, Udaipur. The college already have a machine which extracted pulp from the custard apple. The drying experiments was carried in natural circulation solar dryer. The samples was spread evenly in thin layers on the drying tray and then place on the shelf of the drying chamber. The ambient and drying air temperatures, relative humidities, air velocities and solar radiation were measured.

Drying Kinetics
Moisture content during drying: Moisture content during drying was calculated (Brooker *et al.*, 1974) by determining the ratio of loss of moisture to sample weight.
Drying rate: The drying rate was calculated by estimation of loss of moisture per unit time per unit dry matter (Brooker *et al.*, 1974) [2].
Moisture diffusivity: Diffusivity is influenced by shrinkage, case hardening during drying, moisture content and temperature of material (Singh, 2001b; Karim and Hawaldar, 2005) [14, 7].

The falling rate period in drying of biological materials is best described by simplified mathematical Fick's second law diffusion (Crank, 1975) as given below.

$$\frac{\delta M}{\delta t} = D\frac{\delta^2 M}{\delta X^2} \quad (1)$$

Where, D is diffusion coefficient, X is characteristic dimension i.e. distance from the center.

The solution of Eqn. 1 was obtained considering finite slab geometry of the sample (2×2×1 size) (Crank, 1975). Eqn 1 can be written for infinite slab as follows,

$$\frac{M - M_e}{M_0 - M_e} = MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\pi^2 D_{eff}\, t\left[\frac{1}{L_x^2} X \frac{1}{L_y^2} X \frac{1}{L_z^2}\right]\right] \quad (2)$$

Where,

D_{eff} = Effective diffusivity in m^2/s,

MR = Moisture ratio, dimensionless

M= Moisture content g water per g dry matter

M_0= Initial moisture content, g H_2O/g dry matter

M_e = Equilibrium moisture content, g H_2O/g dry matter

L= Characteristic dimension i.e. thickness of slab

T = Time elapsed during the drying (s).

The equation can be simplified to the first term of the series only and results into following eqn.

$$MR = \frac{8}{\pi^2}\exp\left(-\pi^2 D_{eff}\, t\left[\frac{1}{L_x^2} X \frac{1}{L_y^2} X \frac{1}{L_z^2}\right]\right) \quad (3)$$

Taking logarithm and rearranging as,

$$\ln[MR] = \ln\frac{8}{\pi^2} - \pi^2 D_{eff}\left[\frac{1}{L_x^2} X \frac{1}{L_y^2} X \frac{1}{L_z^2}\right] \quad (4)$$

$$\ln[MR] = -0.21 - \pi^2 D_{eff}\left[\frac{1}{L_x^2} X \frac{1}{L_y^2} X \frac{1}{L_z^2}\right] \quad (5)$$

A general form of above eqn. representing straight line could be written in semi-logarithmic form, as follows.

$$\ln(MR) = A - Bt \quad (6)$$

Where, A is intercept and B is slope of the straight line.

An experimental value of the effective diffusivity is typically calculated by plotting experimental drying data in terms of ln (*MR*) versus drying time t. It gives a straight line and the slope of the line would be used to measure the moisture diffusivity (Eqn 7). This approach is a simplified one and shrinkage of the material is not taken into consideration, i.e. thickness of the material L is assumed constant throughout the drying process.

$$\text{Slope} = \pi^2 D_{eff}\left[\frac{1}{L_x^2} X \frac{1}{L_y^2} X \frac{1}{L_z^2}\right] \quad (7)$$

Mathematical models under study

Modeling of the drying process is important for characterizing the process with different drying methods and conditions. Drying curves were obtained for the custard apple pulp sample with four different moisture ratio models given in Table 1. The moisture ratio (MR) was estimated from the ratio $(M-M_e)/(M_0-M_e)$, using the final moisture content of the dehydrated product as the equilibrium moisture content (Me). M_0 is initial moisture content and M is moisture content at any time t, expressed on a dry basis. The correlation coefficient (R^2) was one of the primary criteria used to select the best equation to account for the variation in the drying curves of the samples. The constants of the selected models were estimated by non-linear regression. The proposed models were fitted on the experimental data using linear regression. The statistical parameters, standard square error (SSE) and root mean square error (RMSE), were estimated by using MATLAB version 13.0 software packages (Ramachandra and Rao, 2009) [10].

Table 1: Mathematical models used under drying study

S. No	Model Name	Model	References
1	Lewis	$MR = \exp(-kt)$	Bruce (1985)
2	Page	$MR = \exp(-kt^n)$	Page (1994)
3	Logarithmic	$MR = 1 + at + bt^2$	Togrul and Pehlivan (2004)
4	Wang and Singh	$MR = a\exp(-kt) + c$	Wang and Singh (1978)

Where, k is drying rate constant, t is drying time (min), n is dimensionless empirical coefficient, a, b, c are empirical constants in drying models.

Results and Discussions

Drying characteristics of custard apple pulp

The average initial moisture content of the custard apple pulp was 66.8 per cent (wb) which was dried to final moisture content of 9.58 per cent (wb). The variations in moisture content with time during the drying period is presented in Fig. 2. The moisture content decreased exponentially with drying time. The figure clearly shows that the maximum moisture loss was observed during first 9 h and decreases with the progress in the drying process. The drying followed a typical trend of drying behaviour for food materials as reported earlier (Singh, 2001a) [14]. The average drying time required to lower the moisture of custard apple pulp from initial (66.8 % (wb)) to equilibrium moisture content (9.58 % (wb)) was found to be 29h.

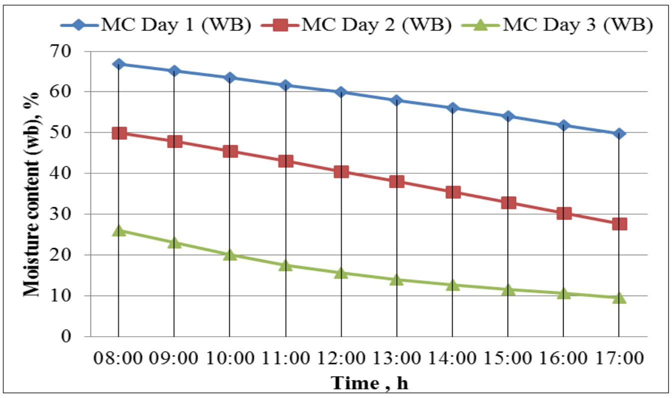

Fig 2: Variation in moisture content of custard apple pulp with drying time

Drying of custard apple pulp occurred only in falling rate period throughout the drying process. The final moisture content of custard apple pulp sample was recorded as 9.58 per cent (wb).

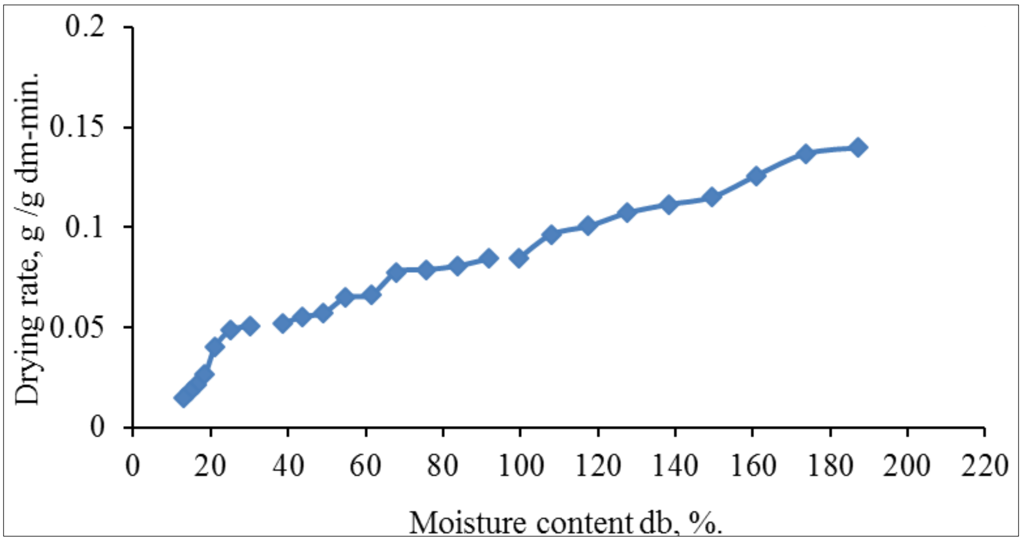

Fig 3: Variation in drying rate of custard apple pulp with moisture content

Moisture diffusivity of custard apple pulp

Effective diffusivities are typically determined by plotting experimental drying data in terms of ln(MR) versus time. The effect of air temperatures on effective moisture diffusivity is generally described using Arrhenius type equation (Akpinar *et al*., 2003) [1]. The moisture ratio (MR) was plotted with drying time in order to find out moisture diffusivity for custard apple pulp in Fig. 4. The variation in ln (MR) with drying time for case was found to be linear with inverse slope. At the level, straight lines fitted well with coefficient of correlation (r) as 0.973. Moisture diffusivity was calculated using Eqn (7) from the slope of the straight line (Maskan *et al.*, 2002) [8] and is presented in Table 2. The effective moisture diffusivity was 9.12816E-07 m²/s during drying of custard apple pulp.

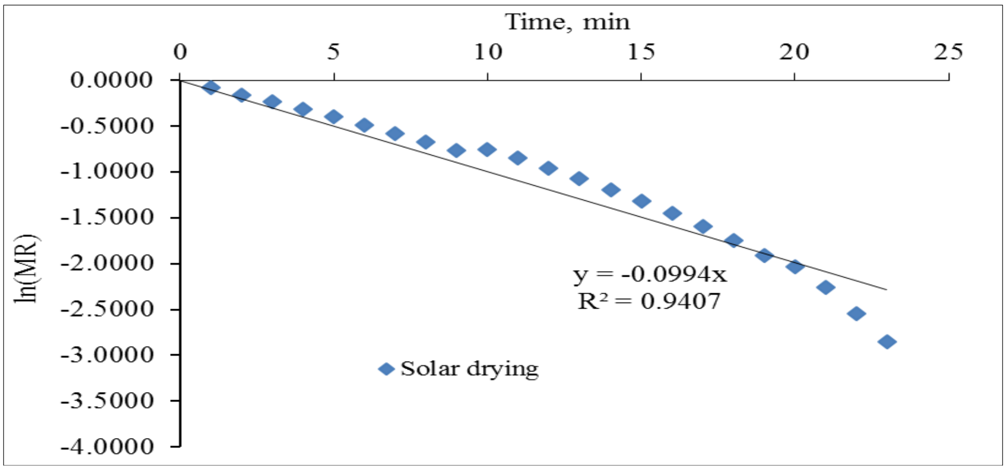

Fig 4: Variation in ln (MR) versus time for solar drying of custard apple pulp

Table 2: Moisture diffusivity of custard apple pulp drying

Equation of straight line y = mx + c	Diffusivity, m^2/s	R
y = -0.099	9.12816×10^{-7}	0. 973

Mathematical modeling of drying of custard apple pulp

Four drying models namely Page, Lewis, Logarithmic and Wang and Singh, were selected based on their ability to best fit the experimental data. The constants and parameters of all the models were estimated by using MATLAB 13.0. Among these models, the best model suitable to fit the data was selected on the basis of highest value of coefficient of determination (R^2) and the lowest value of standard square error (*SSE*) and root mean square error (*RMSE*). The estimated values of statistical parameters *viz*., coefficient of determination (R^2) and root mean square error (*RMSE*) are shown in Table 3. It was observed that the values of coefficient of determination (R^2) for Logarithmic model at solar drying temperature was 0.998 and root mean square error (RMSE) was 0.016217 which were lower than the rest of other. Hence, Logarithmic model was found best fit than the other models to represent the drying of custard apple pulp. The selected Logarithmic model for solar drying studies was validated by comparing the predicted and observed values of moisture ratio in drying experiment. The predicted and observed value of moisture ratio is shown in Fig. 5.

Table 3: Values of coefficients for various models and their statistical parameters for drying of custard apple pulp

Name and equation of model	Drying model constant					Statistical parameters		
	k	n	a	b	c	$\chi 2$	R2	RMSE
Lewis model $\exp(-kt)$	0.09098	-	-	-	-	0.00213	0.9768	0.045369
Wang and Singh model $1+at+bt^2$	-	-	-0.066	0.0011	-	2.82x10-4	0.99704	0.016217
Page model $\exp(-kt^n)$	0.05031	1.2315	-	-	-	9.0258x104	0.9905	0.029023
Logarithmic model $a\exp(-kt)+c$	0.05993	-	1.23129	-	-0.236	1.79x10-4	0.99819	0.012675

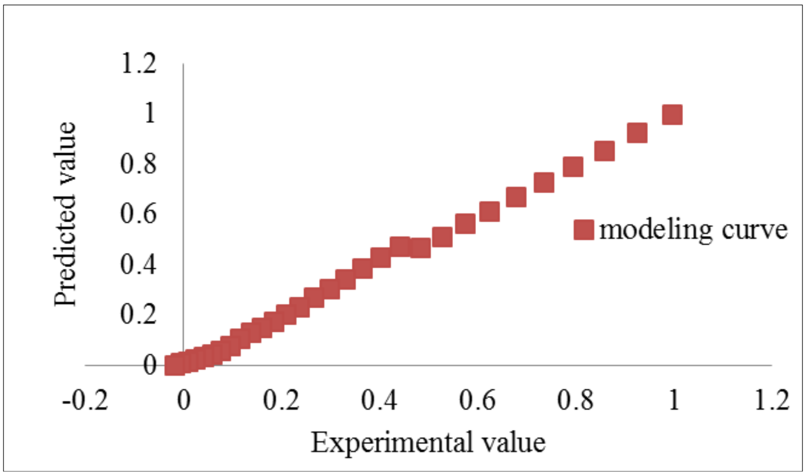

Fig 5: Experimental and predicted values of moisture ratio by Logarithmic model for drying of custard apple pulp

Conclusion

Solar drying was used for drying of custard apple pulp, the drying time was found 29h whereas the moisture diffusivity was $9.12816x10^{-07}$. No constant rate period was found during drying and whole drying process took place in the falling rate period only. Among the all model studied, Logarithmic model gave better predictions and satisfactorily described the characteristics of custard apple pulp.

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