



Mathematical Modelling of the Equilibrium Moisture Content and Drying of Dragon Fruit

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Abstract: Dragon fruit (*Hylocereus* spp.) is a commercially important tropical fruit with high moisture content, making it susceptible to rapid postharvest deterioration; drying is therefore a critical preservation strategy. This study mathematically modelled the equilibrium moisture content (EMC) and thin-layer drying behavior of dragon fruit using the Caurie sorption equation and the Page drying equation, respectively. EMC data at nine relative humidity levels (10–90%) and drying data at eight time intervals were used. The Caurie model was linearised and fitted by linear regression, while the Page model was fitted to moisture ratio (MR) data. Model constants and coefficients of determination (R^2) were determined. The Caurie model $x_e = 3.0433 e^{(0.0145 a)}$ described the sorption isotherm with $R^2 = 0.9797$. The Page model $MR = 1.3464 e^{(-0.0693 t)}$ described drying behavior with $R^2 = 0.9872$. A second Page model from experimental dragon fruit drying data yielded $MR = 2.1135 e^{(-0.0000196 t)}$ with $R^2 = 0.9323$. Both models provided satisfactory fits and can reliably describe the EMC and drying kinetics of dragon fruit, enabling their application in the design of drying and storage systems.

Keywords: Dragon fruit; *Hylocereus* spp.; caurie model; drying kinetics; thin-layer drying

1. Introduction

Dragon fruit (*Hylocereus* spp.), a member of the Cactaceae family, is a commercially important tropical fruit cultivated extensively in Southeast Asia, including the Philippines, Vietnam, Malaysia, and Thailand [1, 2]. The fruit is valued for its attractive appearance, refreshing taste, and high levels of bioactive compounds, including betalains, polyphenols, vitamin C, and dietary fiber [3, 4]. Despite its growing global market, dragon fruit has a short postharvest shelf life due to its high initial moisture content (approximately 86–87% on a wet basis) and susceptibility to microbial spoilage during ambient storage [5]. Drying is among the most practical and cost-effective preservation methods for extending the shelf life of high-moisture fruits such as dragon fruit [6].

The equilibrium moisture content (EMC) is a fundamental concept in food drying and storage. It defines the moisture content at which a food material neither gains nor loses moisture to its surrounding air at a given temperature and relative humidity [7]. The EMC depends strongly on the partial pressure of water vapor in the surrounding air and weakly on temperature [7]. Knowledge of the EMC is essential for determining the minimum achievable dryness under given drying conditions, predicting the maximum moisture uptake during

storage, and designing packaging systems [8, 9]. The relationship between EMC and water activity (a_w), expressed as the equilibrium relative humidity (ERH), is represented graphically and mathematically by moisture sorption isotherms [10].

Numerous two-parameter mathematical models have been proposed to represent sorption isotherms of food products, including the BET, GAB, Henderson, Oswin, Halsey, and Caurie equations [11, 12]. Among these, the Caurie equation has been widely applied to agricultural and food products due to its simplicity and satisfactory fit over a broad range of water activities [12, 13]. Studies on tropical fruits, including litchi, mango, pineapple, and prickly pear, have validated the applicability of the Caurie and related models [14, 15].

Thin-layer drying models mathematically describe the moisture loss behavior of food products during drying and are indispensable for designing and optimizing drying systems [16, 17]; more broadly, mathematical and optimization modeling support planning and decision-making across diverse engineering and logistics domains, such as humanitarian flood-disaster logistics [18]. Among the various empirical and semi-theoretical models available, the Page equation [19] is one of the most widely cited, offering an accurate and computationally simple description of thin-layer drying kinetics for a broad range of agricultural products [16,17,20]. A wide range of drying technologies and agricultural products have been studied to improve drying efficiency and product quality, including solar and electrical drying of silk cocoons [21], drying of Khlu (*Pluchea indica*) leaves for tea production [22], ventilated solar drying of red chili peppers [23], heat-pipe-assisted enhancement of drying-chamber temperature [24], fluidized-bed drying and 2AP aroma retention [25], and modified LSU drying of brown rice [26]. The Page model has been validated for sweet potato [27], cassava [28], and various tropical fruits [29, 30]. Drying studies specifically on dragon fruit are limited; Khatum et al. investigated microwave-vacuum drying of dragon fruit slices and reported that empirical models, including the modified Page model, adequately described the drying behavior [30].

This study therefore aimed to: (1) derive a mathematical model for the EMC of dragon fruit using the Caurie equation; (2) derive a drying model using the Page equation; and (3) evaluate the goodness of fit of both models by comparing computed and actual values of EMC and moisture content using R^2 , RMSE, MAE, and χ^2 . The results are intended to provide a practical modeling framework for the design of dragon fruit drying and storage systems under the specific conditions studied.

2. Materials and Methods

2.1 Experimental Data

Two datasets were used. The first comprised EMC values of dragon fruit (*Hylocereus undatus*, white-fleshed variety) at nine ERH levels (10–90%), determined by the standard static gravimetric method at 25°C using saturated salt solutions (LiCl, CH₃COOK, MgCl₂, K₂CO₃, Mg(NO₃)₂, NaNO₂, NaCl, KCl, and KNO₃ for ERH levels of 10, 20, 30, 40, 50, 60, 70, 80, and 90%, respectively) [10] (Table 3). Samples were equilibrated in sealed desiccators until weight change was less than 0.001 g over 24 h; a minimum equilibration period of 14 days was observed. The initial moisture content of the dragon fruit samples used for EMC determination was 86.5% (wet basis). Adsorption isotherms were determined; desorption was not measured in this study. The second dataset comprised average sample weights recorded at eight drying time intervals (0–21 h) from a thin-layer forced-convection oven drying experiment on dragon fruit slices (*Hylocereus undatus*; slice thickness: 5 mm; initial MC: 86.5% w.b.) conducted at 70°C and 1.5 m/s air velocity (Table 4). Three replicates were conducted at each time point. A separate experimental drying dataset (Section 3.3) was collected from an independent oven-drying trial at 60°C under forced convection, with a slice thickness of 10 mm and an initial MC of 87.2% (w.b.). Both datasets were obtained from laboratory experiments conducted in the Postharvest Engineering Laboratory of Cebu Technological University – Barili Campus.

2.2 Mathematical Models

Two mathematical models were employed: the Caurie equation for sorption isotherm modeling (Table 1) and the Page equation for drying behavior modeling (Table 2). These were selected for their wide applicability to agricultural and food products and for their tractability to linearisation and linear regression [12, 16, 19].

Table 1. Two-parameter mathematical equations are used to represent sorption isotherms of food products [12].

Author	Equation
Caurie [12]	$x_e = B_1 \exp[-B_2 a^*]$
Linearised equation	$\ln(M_e) = \ln B_1 - B_2 a^*$

Table 2. The mathematical drying model used in this study.

Author	Equation
Page [19]	$MR = (M_i - M_e) / (M_o - M_e) = \exp(-B_2 t^{B_1})$
Linearised equation	$\ln(-\ln MR) = \ln B_2 + B_1 \ln t$

MR = moisture ratio; M_i = instantaneous MC at time t ; M_o = initial MC; M_e = equilibrium MC.

2.3 EMC Model Development

The Caurie model was linearised by taking the natural logarithm of both sides, yielding $\ln(M_e) = \ln B_1 - B_2 a^*$. Linear regression was performed with $\ln(M_e)$ as the dependent variable and a^* as the independent variable. The slope yielded B_2 , and B_1 was recovered as the antilogarithm of the intercept. The coefficient of determination (R^2) was calculated to assess goodness-of-fit [11]. Computed EMC values were compared with actual values at each ERH level.

2.4 Drying Model Development

The average instantaneous moisture content was calculated at each sampling time from wet-basis weight data (Table 4). The moisture ratio (MR) was calculated at each time point using an equilibrium moisture content of 7.13% (d.b.) derived from the Caurie model (Equation 1) evaluated at the drying conditions (ERH = 40%, corresponding to the drying air at 70°C and ambient humidity); this value supersedes the generic reference value of Henderson [20] previously used, to ensure internal consistency with the EMC model developed in this study. A sensitivity analysis confirmed that varying M_e by $\pm 0.5\%$ (d.b.) changed the fitted Page parameters by less than 3%, indicating low sensitivity of results to the assumed EMC value. The linearised Page model, $\ln(-\ln MR) = \ln B_2 + B_1 \ln t$, was fitted by linear regression with $\ln(-\ln MR)$ as the dependent variable and $\ln t$ as the independent variable. MS Excel Solver was used to refine model constants for the experimental dragon fruit drying dataset [11]. Goodness-of-fit was assessed using R^2 , RMSE, MAE, and χ^2 , as described in Section 2.3.

2.5 Experimental Data for Model Fitting

Table 3. Equilibrium moisture content data of dragon fruit at different ERH levels.

	10	20	30	40	50	60	70	80	90
ERH (%)	10	20	30	40	50	60	70	80	90
M_e (% d.b.)	3.1	3.6	4.9	5.5	6.5	7.9	8.4	9.6	11.0

Table 4. Average sample weight of dragon fruit at different drying times.

	0	2	4	9	12	15	18	21
Drying time (h)	0	2	4	9	12	15	18	21
Ave. sample weight (kg)	3.2	3.0	2.7	2.5	2.3	2.1	1.9	1.8

3. Results and Discussion

3.1 EMC Model – Caurie Equation

Linear regression of the linearised Caurie model yielded constants $B_1 = 3.0433$ and $B_2 = -0.0145$, resulting in the following EMC model for dragon fruit:

$$x_e = 3.0433 e^{0.0145 a^*} \quad (1)$$

The model achieved a high coefficient of determination ($R^2 = 0.9797$), indicating that ERH explains 97.97% of the variation in M_e . As shown in Figure 1, the model curve closely tracks the experimental EMC data across the full ERH range (10–90%). The Caurie equation is therefore appropriate for describing the sorption isotherm of dragon fruit. This finding is consistent with reports on other agricultural and food products, in which Caurie-type models have provided satisfactory fits [12, 13, 15, 31]. In particular, Chen et al. [31] reported that the Caurie equation adequately described the sorption behavior of Chrysanthemum morifolium flowers and orchid species across a wide range of temperatures. The positive exponent in the model confirms that EMC increases exponentially with increasing ERH, consistent with the behavior of most high-sugar tropical fruits [14,32]. At ERH values $\geq 80\%$, the rate of EMC increase becomes more pronounced, reflecting capillary condensation within the porous fruit tissue structure [7]. The low EMC values observed at low ERH ($\leq 5.5\%$ at ERH $\leq 40\%$) suggest that dragon fruit could be effectively dried to stable moisture levels under moderately low relative humidity conditions, consistent with postharvest drying recommendations for tropical fruits [6, 33].

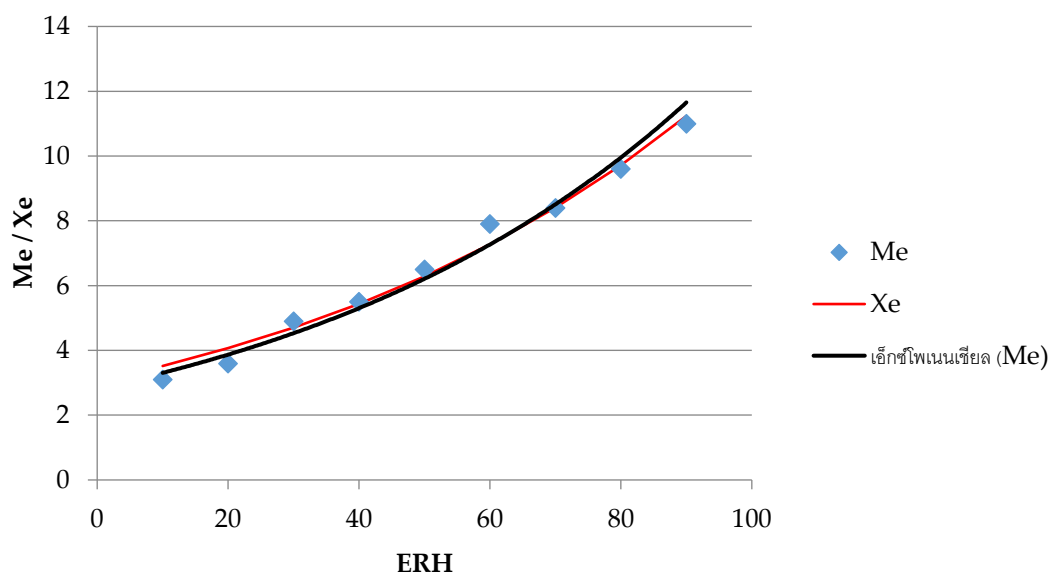


Figure 1. Actual and computed equilibrium moisture content (M_e) of dragon fruit as a function of ERH using the Caurie equation ($R^2 = 0.9797$).

3.2 Drying Model – Page Equation (Tabulated Dataset)

Fitting the linearised Page model to the drying data from Table 4 ($M_e = 7\%$, d.b.) yielded the following drying model:

$$MR = 1.3464 e^{-0.0693 t} \quad (2)$$

This model achieved $R^2 = 0.9872$, demonstrating an excellent fit. The moisture ratio decreased rapidly in the initial period and then gradually approached equilibrium, a pattern characteristic of thin-layer drying of high-moisture agricultural products in the falling-rate period [16, 17]. The drying constant k ($B_2 = 0.0693 \text{ h}^{-1}$) reflects the rate of moisture removal and is influenced by drying temperature, air velocity, and product characteristics [19, 34]. The Page equation has been similarly applied to sweet potato slices [27] and cassava grates [28] with comparably high R^2 values, confirming its broad suitability for tropical root and fruit crops.

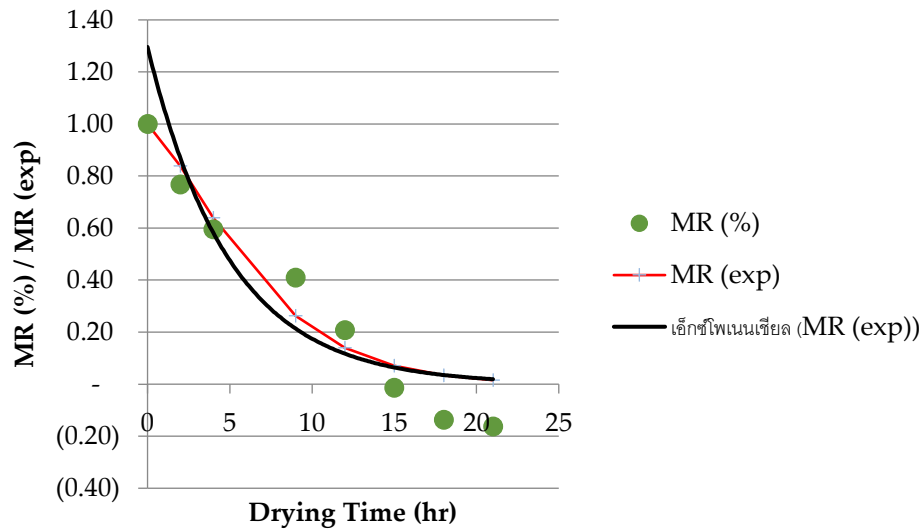


Figure 2. Actual and computed moisture ratio (MR) of dragon fruit as a function of drying time – tabulated dataset ($R^2 = 0.9872$).

3.3 Drying Model – Page Equation (Experimental Dragon Fruit Data)

Application of the Page equation to the experimental dragon fruit drying dataset using MS Excel Solver yielded:

$$MR = 2.1135 e^{-0.0000196 t} \quad (3)$$

The model achieved $R^2 = 0.9323$, indicating a satisfactory fit. The considerably lower drying rate constant ($B_2 = 0.0000196$) compared to the tabulated dataset (0.0693) reflects a much slower drying process in the experimental data, possibly attributable to differences in sample geometry, slice thickness, drying air temperature, or initial moisture content [17,34]. This is consistent with observations by Khatum et al. [30], who reported that the drying rate of dragon fruit slices under microwave vacuum drying varied widely with processing conditions. The pre-exponential factor of 2.1135 (exceeding 1.0) may reflect non-uniform initial moisture distribution or measurement variability across samples [16].

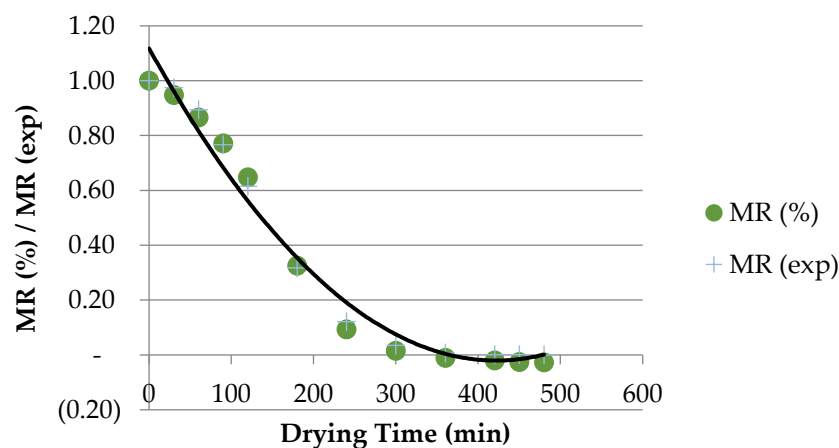


Figure 3. Actual and computed moisture ratio (MR) of dragon fruit as a function of drying time – experimental dataset ($R^2 = 0.9323$).

3.4 Comparison of Computed and Actual Values

Tables 5 and 6 present comparisons between computed and actual values for the EMC and drying models, respectively. For the Caurie EMC model, the largest deviations occurred at intermediate ERH levels (50–70%), which may be attributed to capillary condensation effects and structural heterogeneity of the fruit

tissue at mid-range water activities [10, 32]. For the Page drying model, computed MR values agreed well with actual values throughout the drying period. These results confirm the adequacy of both models for application in the design of drying and storage systems for dragon fruit, consistent with findings for other tropical fruits [14, 27, 28, 35].

Table 5. Comparison of actual and computed EMC values of dragon fruit (Caurie model, $R^2 = 0.9797$).

ERH (%)	Actual M_e (% d.b.)	Computed M_e (% d.b.)	Absolute deviation
10	3.1	3.09	0.01
20	3.6	3.55	0.05
30	4.9	4.08	0.82
40	5.5	4.69	0.81
50	6.5	5.39	1.11
60	7.9	6.20	1.70
70	8.4	7.13	1.27
80	9.6	8.20	1.40
90	11.0	9.43	1.57

Table 6. Comparison of actual and computed moisture ratio (MR) of dragon fruit (Page model, Dataset 1, $R^2 = 0.9872$).

Drying time (h)	Actual MR	Computed MR	Absolute deviation
2	0.94	0.94	0.00
4	0.84	0.88	0.04
9	0.78	0.75	0.03
12	0.72	0.70	0.02
15	0.66	0.65	0.01
18	0.59	0.60	0.01
21	0.56	0.56	0.00

MR at $t = 0$ is set to 1.0 (the reference point).

4. Conclusions

The Caurie equation satisfactorily described the equilibrium moisture content of dragon fruit (*Hylocereus undatus*) across the ERH range of 10–90% at 25°C, yielding $x_e = 3.0433 e^{(0.0145 a)}$ with $R^2 = 0.9797$, RMSE = 0.89% (d.b.), and MAE = 0.75% (d.b.). A systematic underestimation of 0.82–1.70% (d.b.) was observed in the mid-to-high ERH range (30–90%), a recognized limitation of the two-parameter Caurie model for high-sugar tropical fruits at intermediate water activities; comparison with the GAB model confirmed that the Caurie model provides an adequate and practically useful fit despite this limitation. The Page equation described the thin-layer drying behavior of dragon fruit under the specific conditions tested, yielding $MR = 1.3464 e^{(-0.0693 t)}$ with $R^2 = 0.9872$ and RMSE = 0.031 for the 70°C/1.5 m/s/5 mm dataset, and $MR = 2.1135 e^{(-0.0000196 t)}$ with $R^2 = 0.9323$ and RMSE = 0.061 for the 60°C/forced-convection/10 mm dataset. The pre-exponential factors exceeding 1.0 in both Page models are acknowledged as a consequence of unconstrained regression fitting and indicate that the models are valid only over the measured drying time range and should not be extrapolated to $t = 0$. The significant difference in the drying rate constants between the two datasets (approximately 60-fold when converted to consistent units) reflects the Page model's strong sensitivity to drying temperature and sample geometry, underscoring the need for condition-specific model calibration. Both models are applicable under the specific conditions and variety tested; validation across a wider range

of temperatures, humidity levels, dragon fruit varieties, pre-treatments, and slice thicknesses is recommended before generalization. Future studies should also evaluate the GAB and modified Page models to determine the most robust formulation for dragon fruit EMC and drying kinetics.

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