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MOISTURE DESORPTION OF FRESH *CORCHORUS OLITORIUS* LEAVES: COMPARATIVE EMPIRICAL AND STATISTICAL MODELLING WITH OPTIMIZATION OF STORAGE CONDITION

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Abstract

This study aimed to characterize the moisture desorption characteristics of fresh *Corchorus olitorius* leaves, comparatively analyse the isotherms with empirical and statistical models, and determine its optimal storage conditions for fresh state shelf stability. Fresh leaves were equilibrated in microclimates generated with saturated salt solutions, producing relative humidity (RH) levels from 7% to 89% at temperatures of 30°C, 40°C, and 50°C. Mass measurements were recorded until equilibrium moisture content (M_{equ}) was reached. The experimental data were analysed using three empirical models, and Response Surface Methodology (RSM) statistical model. In addition, RSM was utilized to evaluate the effects of temperature and RH on M_{equ} with

complimentary process optimization. The GAB model outperformed the LESAM, Peleg and RSM statistical models, with R^2 values of 0.9825 at 30°C, 0.9966 at 40°C, and 0.9991 at 50°C. RSM model analysis identified an optimal storage condition at 30°C and 89.50% RH, predicting a M_{equ} of 65.38% (d.b.) with a desirability score of 0.851. It is concluded that maintaining lower temperatures with high relative humidity significantly enhances moisture retention in *C. olitorius* to sustain freshness or shelf stability. These findings offer framework for postharvest handling, aiming to extend shelf life of *C. olitorius* for fresh state marketing.

Keywords: *Corchorus olitorius* leave, Moisture Desorption, Sorption Isotherm, Modelling, Optimization

Introduction

Corchorus olitorius is a staple vegetable diet in several regions due to its easy of cultivation, relatively short crop cycle, rich nutritional profile and diverse therapeutic properties

(Maroyi *et al.*, 2024). Despite its health benefits and culinary versatility, *C. olitorius* is highly perishable due to its high initial moisture content that enables rapid microbial spoilage, enzymatic degradation, and nutrient losses after harvesting, during marketing and display, and storage. In

Nigeria, *Corchorus olitorius* with high visual appeal is preferred by consumers and is typically sold and processed in its fresh, un-dried state; therefore, vendors frequently mist the leaves and store them in cool conditions throughout the marketing period to preserve its original moisture content and maintain its marketability. Hence, preserving *Corchorus olitorius*'s visual quality, marketability and extending its shelf life in the fresh state requires a deeper understanding and effective control of its moisture desorption characteristics.

Moisture sorption isotherms are graphical description of the equilibrium relationship between a material's moisture content and water activity or relative humidity at a given temperature (Labuza & Altunakar, 2020). These representations explain the water–matrix interactions that govern the stability, safety, and quality of food products (Iglesias & Chirife, 1982). The moisture sorption characteristics not only influence microbial growth and chemical reactions but also affects textural properties, consumer acceptability and the retention of bioactive compounds. Empirical models have long been applied to describe moisture isotherms (Zhang *et al.*, 2022). Among these, the Guggenheim–Anderson–de Boer (GAB) model is versatile for its ability to predict equilibrium moisture content over a broad range of water activities (Ennoukh *et al.*, 2022). Other models, such as the Peleg and Enderby models have also been employed in various studies (Ojike *et al.*, 2021). Generally, these models serve as tools in representing, analysing and predicting moisture uptake and are utilized in the design of drying

systems and packaging materials or conditioned that are tailored to the unique characteristics of each specific product (Zhang *et al.*, 2022). In parallel to empirical modelling, statistical techniques such as Response Surface Methodology (RSM) have been established as a powerful tool for process modelling and optimization (Allouss *et al.*, 2019). RSM can enable the determination of the interactive effects of multiple variables (Candioti *et al.*, 2014), which are temperature and relative humidity, in the case of moisture sorption characteristics. RSM can also deliver conditions that minimize or maximize the isotherm (Adeyi *et al.*, 2024) and consequently reduce the risks associated with microbial spoilage, quality degradation and thus visual appeal in marketing. For *C. olitorius*, where postharvest losses can significantly impact economic returns (to the farmers and agribusiness entrepreneurs) and nutritional quality (to the populace), such an approach is particularly relevant.

Despite the abundance of research on moisture sorption in fruits, cereals, and other leafy vegetables (Ojike *et al.*, 2021 and Zhang *et al.*, 2022), there is a notable gap regarding *C. olitorius*. Limited studies have focused specifically on its sorption characteristics, and even fewer have applied a combined empirical and statistical modelling approach and determine its optimal holding or storage conditions for freshness and marketability, quality preservation and visual appeal. Given the high perishability of *C. olitorius*, it is imperative to investigate its moisture characteristics to ensure that storage processes are efficient and economically viable.

The current study addresses this gap by pursuing four primary objectives, which are, to determine the moisture sorption isotherms of *C. olitorius* experimentally using a static gravimetric method over a range of temperatures (30, 40, and 50 °C) and relative humidity levels, fit the experimental data to three empirical models, utilize Response Surface Methodology (RSM) approach to statistically model the interactive effects of temperature and relative humidity on moisture desorption and identify the optimal storage conditions that enhance freshness (that is, storage at lowest moisture desorption characteristics) of *C. olitorius*.

Materials and Methods

Materials

Fresh leaves of *C. olitorius* were collected from natural habitat in Ogbomoso Township, Oyo State, Nigeria (Latitude 8°2'35.56"N to 8°13'22.44"N, Longitude 4°9'17.64"E to 4°20'5.64"E). A weighing balance (± 0.001 g accuracy), a Stangas SG-9052G oven (manufactured by Stangas Luxury Modern Appliances, Italy), and glass jars were utilized to measure, dry, and equilibrate the leaf samples, respectively. Only intact, undamaged leaves were chosen for the study. *C. olitorius* leaves were picked, rinsed with distilled water, air-dried at ambient temperature (28 – 30 °C) for 1 hour, before being subjected to equilibration within prepared saturated microclimates.

Experimental Procedures

The equilibrium moisture content (M_{equ}) of *C. olitorius* leaves were determined at varied

temperatures (30, 40, and 50°C) using a gravimetric method (Saad *et al.*, (2014).). The method employed utilization of saturated salt solutions to establish controlled microclimates. Six salts, including, potassium nitrate, sodium chloride, magnesium chloride, potassium chloride, potassium bromide, and magnesium nitrate, were dissolved in 200 ml of distilled water till saturation. Six 1-ltr glass jars with airtight lids were prepared; each filled to one-quarter capacity with a saturated salt solution, ensuring residual undissolved salt remained throughout equilibration. A wire mesh platform was positioned within each jar to suspend leaf samples above the solution (Adeyi, 2024).

These solutions generated relative humidity (RH) levels ranging from 7% to 89%. Precisely weighed leaf samples (0.2 g ± 0.001 g) were placed in the jars, which were then sealed and transferred to temperature-controlled ovens (30, 40, or 50°C). Daily mass measurements were recorded until equilibrium (constant mass) was attained. To calculate M_{equ} aided by Eqn. (1), equilibrated samples were removed, oven-dried at 105°C for 24 h, and reweighed to determine dry mass (Heras *et al.*, 2014).

$$M_{\text{equ}}(\% \text{ d.b}) = \frac{m_b - m_a}{m_a} * 100 \quad (1)$$

Where M_{equ} is the equilibrium moisture content in % d.b., m_a and m_b are initial and final sample masses in grams.

Empirical Modelling of Sorption Kinetic

Empirical models offer computational efficiency for rapid model development and analysis,

particularly in studies constrained by limited experimental datasets (Brabanter *et al.*, 1991). In this investigation, three semi-empirical models, each incorporating time (t) as a variable with distinct parametric relationships, were applied to characterize the moisture sorption isotherms of *C. olitorius* leaves. The mathematical formulations and parametric configurations of these models are outlined in Eqn. (2) – (4) (Ennoukh *et al.*, 2022, Zhang *et al.*, 2022, and Abdullah *et al.*, 2023).

$$\text{GAB} = M_{\text{equ}} = \frac{C_m * C_1 * k * a_w}{(1 - k * a_w)(1 - k * a_w + C_1 * k * a_w)} \quad (2)$$

$$\text{LESPAM} = M_{\text{equ}} = A_1 * \text{EXP} \left(\frac{B_1 * a_w}{T} \right) + C_2 \quad (3)$$

$$\text{Peleg} = M_{\text{equ}} = A_2 * a_w^{B_2} + C_3 * a_w^{D_1} \quad (4)$$

Where, C_m = monolayer moisture, C_1 = energy constant, k = correction factor for multilayer adsorption, A_1 , B_2 , C_2 , A_2 , B_2 , C_3 and D_1 = model constants, a_w = water activity, and T = temperature.

The water activity was converted to RH% by multiplying the respective water activities by 100 (Labuza & Altunakar, 2007). Parameter estimation and model fitting were conducted using MATLAB R2014a software, enabling precise estimation of the model parameters.

Statistical Modeling and Optimization of Sorption Kinetic using RSM

This research employed statistical modelling through Design Expert 6 software. Statistical modelling serves as a robust method for analyzing and illustrating the connections

between a continuous dependent variable and multiple independent variables (Hair *et al.*, 2019). It provides a structured approach to understanding complex relationships and optimizing processes effectively.

The statistical model used in this study is represented by Eqn. (5)

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n + \varepsilon \quad (5)$$

Where; the dependent variable (Y) is expressed as a linear combination of the independent variables (X_1 to X_n) and with an error term (ε). The coefficients (β) are the regression coefficients that quantify individual effect of independent variables on the dependent variable, holding all other variables constant (Zeitler, 2015). The error term (ε) accounts for unexplained variance in the data, which could be due to random error, measurement inaccuracies, or the influence of other variables not included in the model (Hair *et al.*, 2019).

In addition, determination of optimum M_{equ} was conducted using RSM to identify the optimal storage temperature and relative humidity for maximizing the hygroscopic capacity of *C. olitorius* leaves that preserves freshness and marketability using desirability method (Adeyi, 2024).

Modelling efficiency

Model performance was evaluated using three statistical metrics: the sum of squared errors (SSE), coefficient of determination (R^2), and root-mean-square error (RMSE). Optimal model fit is indicated by R^2 values approaching 1

(theoretical range: 0 - 1) and minimized SSE and RMSE values. The mathematical expressions for these metrics are provided in Eqn. (6 – 8) (Adeyi, 2024).

$$SSE = \sum_{i=1}^n (\text{Pred}, i - \text{Exp}, i)^2 \quad (6)$$

$$R^2 = 1 - \left(\sum_{i=1}^n \frac{(\text{Pred}, i - \text{Exp}, i)^2}{(\text{Pred}, i - \text{AverageExp})^2} \right) \quad (7)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\text{Exp}, i - \text{Pred}, i)^2}{N}} \quad (8)$$

Where, Pred,i depicts the i_{th} predicted value, Exp,i depicts the i_{th} experimental value and AverageExp depicts the average of all the experimental value. ‘n’ represents the number of observations.

Results and Discussions

Effect of Temperature and Relative Humidity on Equilibrium Moisture Content

The desorption isotherm in this study representing the dependence of equilibrium moisture content (M_{equ}) on relative humidity (RH%) at different temperatures is represented in Figure 1.

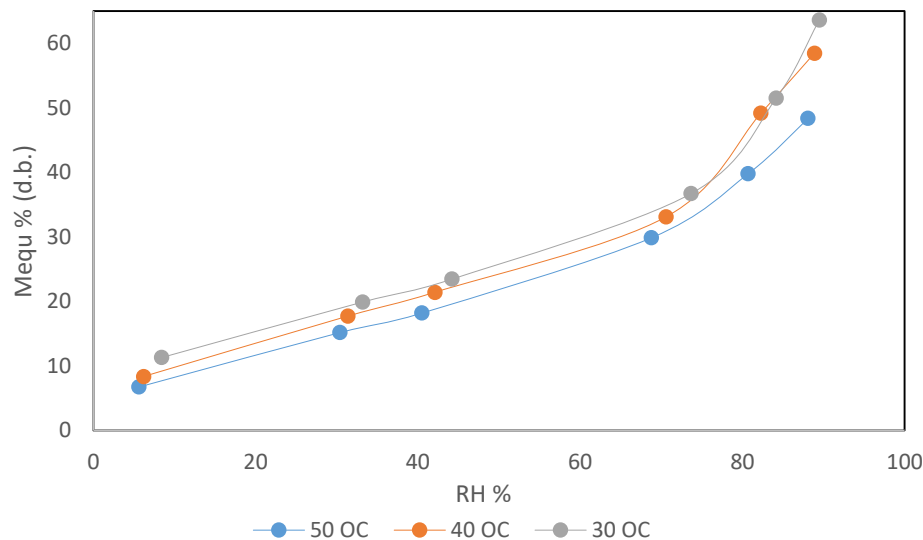


Figure 1: Desorption isotherm of *C. olitorius*

The isotherms in Figure 1 are sigmoidal in shaped and fall to the type II isotherms (Wang *et al.*, (2017). As relative humidity increased, the isotherm depicts that *C. olitorius* leaves adsorbed more moisture, therefore, its equilibrium moisture content increased. This is standard for most hygroscopic materials (Zang *et al.*, 2022). At the same relative humidity, higher temperature curves tend to show slightly lower equilibrium moisture content (Ouafa *et al.*, Adeyi,

2015). This is typical because at higher temperatures, water molecules have more kinetic energy and are less likely to remain adsorbed in the product; hence, the product's equilibrium moisture content is lower (Ennoukh *et al.*, 2022). Usually, most food material exhibit sigmoidal sorption isotherm, commonly classified as Type II (or sometimes Type III for very sugary/amorphous foods) (Polatoğlu *et al.*, 2013). The sigmoidal curve is usually divided

into three regions, including region I (that is, low relative humidity) where water is tightly bound to polar sites in the food (that is, hydroxyl groups in carbohydrates, amino groups in proteins), region II (that is, intermediate relative humidity) where multilayer water begins to form leading to steeply moisture content increment and region III (that is, high relative humidity) where capillary condensation and free water dominate, leading to a rapid rise in equilibrium moisture content (Barbosa-Cánovas, et al., 2007 & Andrade *et al.*, 2011). These result showed that higher equilibrium moisture content is associated to lower temperature and higher

relative humidity. This justifies the misting of *C. olitorius* by vendors to increase its moisture content for freshness, visual appeal and marketability.

Empirical Modelling of Desorption Isotherm of *C. olitorius*

The result of the empirical modeling or analysis of the desorption isotherm characteristics of *C. olitorius* leave is represented in Table 2. The table shows the performance of three empirical models fitted to moisture sorption data of *C. olitorius* leaves at 30, 40, and 50 °C.

Table 2: Performance of the Selected Empirical Models in this Study

Model	Parameter	Temperature		
		30	40	50
GAB	Cm	9.93	8.54	5.98
	C	1.09E5	1.16E5	8.45E4
	k	0.872	0.945	0.9264
	SSE	60.20	33.43	12.32
	R ²	0.9825	0.9966	0.9991
	RMSE	4.061	1.757	0.8334
LESPAM	A	0.1056	0.4636	0.9778
	B	3.509	2.703	2.272
	C	16.82	12.21	8.821
	SSE	79.77	46.33	26.41
	R ²	0.9718	0.9828	0.9884
	RMSE	5.157	3.93	2.967
Peleg	A	9.78e-008	1.969e-005	2.463e-006
	B	4.022	3.01	3.508
	C	0.7627	0.8442	0.903
	D	0.957	0.889	0.8438
	SSE	440.4	308.1	175.9
	R ²	0.8446	0.8855	0.923
	RMSE	14.84	12.41	9.379

Table 2 shows that GAB model outperformed the other two models (that is, LESPAM and Peleg) as indicated by its high R² values (which increased from 0.9825 at 30 °C to 0.9991 at 50 °C) and its correspondingly low SSE and

RMSE. The values of Cm decrease with increasing temperature (9.93 at 30°C, 8.54 at 40°C, and 5.98 at 50°C), indicating reduced water binding capacity at higher temperature (Ojike *et al.*, 2021). The energy constant (C₁),

showed slight increment from 30 – 40°C and a slight decrease from 40 – 50 °C; depicting an almost consistent binding energy for water molecules (Ouafia *et al.*, 2015). The values are high (1.09E5 to 8.45E4), suggesting strong water-material interactions. The correction factor (k) for multilayer adsorption slightly increased as temperature increased reflecting changes in moisture binding dynamics (Wang *et al.*, 2017). The values are close to 1 (0.872 to 0.9264), indicating a good fit to the experimental data. The LESPAM model also provided reasonable fits (that is, R² between 0.9718 and 0.9884) but with higher error indices while the Peleg model gives moderate performance (that is, R² ranging from 0.8446 to 0.923 and higher

RMSE values). In LESPAM model, parameter ‘A’ increased consistently as temperature increased while parameter B and C decreased consistently as the temperature increased. The model parameters in LESPAM and Peleg model have no physical meaning as observed by Zhang *et al.*, (2022), the parameter showed trends that reflect changes in sorption behavior with temperature.

The results confirm the importance of selecting an appropriate model for sorption studies. The GAB model's accuracy in this study makes it a reliable tool for predicting moisture sorption useful for drying, storage, and packaging of *Corchorus olitorius* leaves.

Statistical Modeling of Desorption Isotherm of *C. olitorius*

The statistical (that is, polynomial) model that modelled and predicted the equilibrium moisture content of *C. olitorius* leaves based on two independent variables (A and B) is represented in Eqn. (9).

$$Me_{qu} = +18.8342 - 0.0868*A - 0.28017*B - 1.4963E-003*A^2 + 9.5166E-003*B^2 - 2.44093E-004*A*B \quad (9)$$

Where: A represented temperature (°C), and B represented relative humidity (%).

The Analysis of Variance (ANOVA) of Eqn (10) is represented in Table 3. The table provided deeper understanding into the statistical significance of each term in the model and overall model performance.

Table 3: Performance of the Statistical Model

Source	Sum of Squares	DF Square	Mean Value	F	p-value	Status
Model	7429.195	1485.8434.60		< 0.0001	Significant	
A	54.43	1	54.43	1.27	0.2823	N/Signific.
B	5716.461	5716.46133.12		< 0.0001	Significant	
A ²	0.089	1	0.089	2.083E-003	0.9643	N/Signific.
B ²	696.93	1	696.93	16.23	0.0017	Significant
A*B	0.061	1	0.061	1.419E-003	0.9706	N/Signific.
Residual	515.32	12	42.94			
Cor Total	7944.5117					

R-Squared=0.9351; Adj R-Squared=0.9081; Pred R-Squared=0.8551; Adeq Precision=14.793

Considering the model performance stated in the table, the low p-value (< 0.0001) indicated that the model is significant, meaning at least one term between temperature and relative humidity (or combination of terms) in the polynomial model has a strong influence on the equilibrium moisture content. The p-value of 0.2823 for temperature (that is, term A) showed that temperature is not statistically significant at typical levels (that is, $\alpha = 0.05$). This implied that within the experimental range, the linear effect of factor A does not substantially affect the equilibrium moisture content once other terms are included. In furtherance, the p-value < 0.0001 for relative humidity showed high statistical significance. It indicated that the linear effect of factor B (that is, relative humidity) is a major driver of changes in equilibrium moisture content.

The quadratic term A² has a p-value of 0.9643, indicating that it is not statistically significant. In contrast, the quadratic term B² shows a p-value of 0.0017, which is significant and demonstrates

a non-linear (quadratic) influence of factor B on the response. As factor B changes, the effect on the response deviates from a purely linear trend, indicating a more complex, curved relationship. The interaction term A*B has a p-value of 0.9706, signifying that it is not significant. This implied that the interaction between factors A and B does not substantially affect the response, meaning the effect of one factor on the equilibrium moisture content does not depend heavily on the level of the other factor.

A² (Quadratic) had p = 0.9643, indicating it was not significant, which suggests no meaningful curvature in the response with respect to 'A' within the tested domain. Meanwhile, B² (Quadratic) had p = 0.0017, indicating a significant effect and demonstrating a non-linear (quadratic) influence of factor B on the response, so as B changes, the response does not shift in a purely linear fashion. Finally, A*B (Interaction) had p = 0.9706, which was not significant, implying that the effect of one factor does not depend strongly on the level of the other. The

results assist in process design and control, conforming to the report of Adeyi (2021) and Adeyi (2024).

Empirical and Statistical Model Comparison

This study utilized both empirical and statistical modeling approaches to analyze the moisture equilibrium characteristics of *Corchorus olitorius* leaves. Comparatively, empirical models excelled in describing sorption isotherms, while statistical modelling through RSM provided deeper understanding into interactive effects of temperature and relative humidity on moisture desorption.

The empirical and statistical modelling approaches serve complementary purposes. The empirical models provided mechanistic understanding into moisture sorption behaviour

and allow for parameter estimation, which aids in sorption mechanisms knowledge (Wang *et al.*, 2017). The GAB model, in particular, effectively characterized multilayer sorption dynamics, demonstrating its suitability for hygroscopic materials. Conversely, statistical modelling with RSM enabled a broader evaluation of factor interactions and optimization of storage conditions. While empirical models fit experimental data to predefined equations, RSM allowed for hypothesis-driven analysis, identifying important factors influencing response (that is, moisture desorption). Furthermore, RSM provided predictive capabilities and facilitated decision-making for optimizing postharvest handling strategies. In this study, the empirical model (that is, GAB) had the highest prediction accuracy.

Optimum storage condition for *C. olitorius*

The optimization of storage condition of *C. olitorius* is represented in Figure 2:

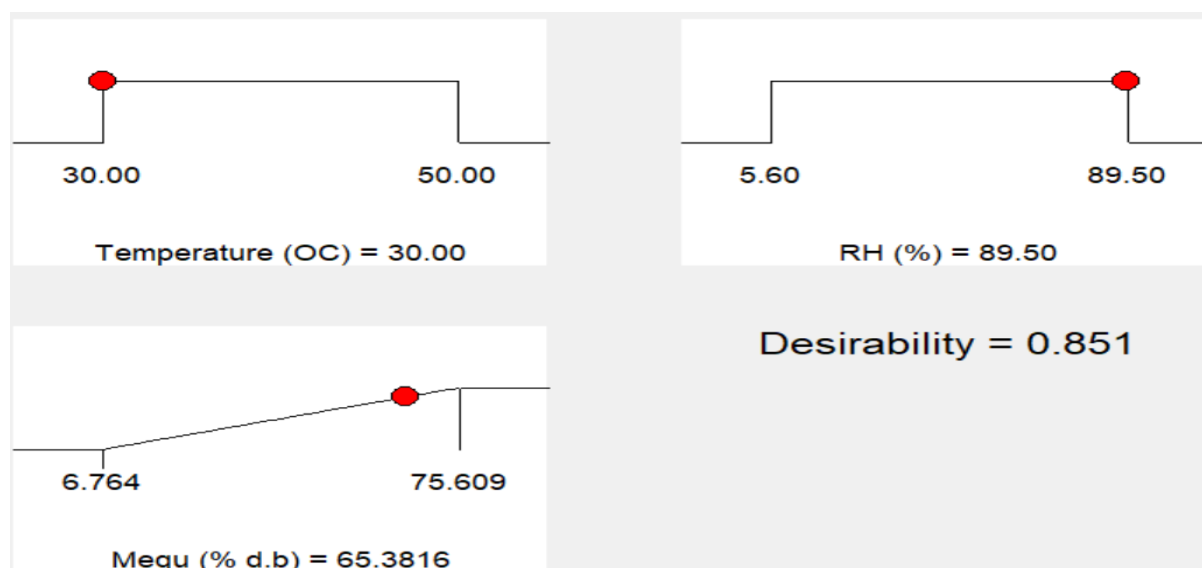


Figure 2: Optimization of *C. olitorius* M_{equ}

The results identified optimal conditions for maximizing M_{equ} in *C. olitorius* while

preserving its visual appeal or freshness, yielding a high desirability score of 0.851.

Specifically, an RH of 89.50% emerged as the most favorable level, since higher humidity supplies additional water vapor that elevates M_{equ} . Meanwhile, the temperature was set to the lower limit of the experimental range (30 °C), aligning with the principle that lower energy levels support moisture retention by reducing water molecule desorption. Under these conditions, M_{equ} is predicted to be 65.3816 % d.b. The high desirability score (0.851) implied the strong alignment of the predicted M_{equ} with the desired outcome at 89.50% RH and 30 °C, indicating that high relative humidity and lower temperatures are advantageous for applications requiring specific moisture content, such as wet-state preservation.

Conclusion

This study characterized the moisture desorption behavior of fresh *Corchorus olitorius* leaves using both empirical and statistical modeling approaches. The experimental data, obtained through controlled gravimetric measurements at varying temperatures and relative humidity

levels, were effectively modeled by the GAB equation, which outperformed alternative models in accurately depicting the multilayer sorption phenomena. Additionally, the application of Response Surface Methodology enabled a detailed analysis of the interactive effects of temperature and relative humidity, leading to the identification of optimal storage conditions. Specifically, maintaining a lower temperature (30 °C), with a high relative humidity (89.50%), was found to maximize the equilibrium moisture content, thereby potentially extending the shelf life and preserving the marketability of the leaves. These findings provide a necessary background for postharvest handling strategies, offering both mechanistic insight and practical guidelines for minimizing spoilage in *C. olitorius* leaves.

Declaration of Conflict of interest

The author declares no conflict of interest on this article.

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