Pertanika J. Trop. Agric. Sci. 49 (S1): 101 - 118 (2026)

TROPICAL AGRICULTURAL SCIENCE

Journal homepage: http://www.pertanika.upm.edu.my/

Moisture Sorption Isotherms and Thermodynamic Characterisation of *Averrhoa bilimbi* (L.) Fruit

La Choviya Hawa[1]*, Mochamad Bagus Hermanto[1], Ubaidillah Ubaidillah[1], Rosnah Shamsudin[2], Lita Puspita R. Perdana[1], Ishika Cherry Nafisa[1], and Nabila Intan Milania[1]

[1]*Department of Biosystems Engineering, Faculty of Agricultural Technology, Universitas Brawijaya, Malang, 65145 East Java Province, Indonesia*
[2]*Department of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*

ABSTRACT

This study investigates the moisture sorption isotherms and thermodynamic properties of *Averrhoa bilimbi* (L.) fruit at the temperature of 25, 35, and 45°C using a gravimetric static method. The equilibrium moisture content (EMC) was measured under adsorption and desorption conditions, and five sorption models (GAB, BET, Peleg, Chung–Pfost, and Halsey) were applied to fit the experimental data. Among these, The BET model exhibited best predictive accuracy based on statistical parameters (R^2, χ^2, RMSE, and mean relative error). This study further evaluated critical water boundaries and calculated the net isosteric heat and sorption entropy using the Clausius–Clapeyron equation. Results demonstrated significant hysteresis between adsorption and desorption isotherms, with higher energy requirements during adsorption due to capillary condensation and bound water dynamics. The findings provide essential insights into the drying behaviour and stability of *A. bilimbi*, which can inform optimised postharvest processing and storage strategies for this highly perishable fruit.

Keywords: Averrhoa *bilimbi*, moisture sorption isotherms, sorption modelling, isosteric heat, thermodynamic properties

ARTICLE INFO

Article history:
Received: 18 July 2025
Accepted: 29 December 2025
Published:

DOI: https://doi.org/10.47836/pjtas.49.S1.05

E-mail addresses:
la_choviya@ub.ac.id (La Choviya Hawa)
mbhermanto@ub.ac.id (Mochamad Bagus Hermanto)
ubaidillah88@ub.ac.id (Ubaidillah)
rosnahs@upm.edu.my (Rosnah Shamsudin)
litapuspita@ub.ac.id (Lita Puspita R. Perdana)
cherrynafisa@ student.ub.ac.id (Ishika Cherry Nafisa)
nabila_nia@student.ub.ac.id (Nabila Intan Milania)
* Corresponding author

INTRODUCTION

Averrhoa bilimbi (L.) is a fruit species widely cultivated in tropical regions such as Indonesia, Malaysia, Sri Lanka, India, Myanmar, Bangladesh, and parts of Central and South America (Mokhtar & Aziz, 2017).

e-ISSN: 2231-8542

The fruit is characterised as small in size, green in colour, and has a sour flavour due to its high oxalic acid contain (Garg et al., 2022). The bilimbi fruit is commonly used in folk medicine due to its medicinal properties (Sarker & Chowdhruy, 2024). The fruit has rich dietary fibre, protein, minerals, anthocyanins, tannins, and vitamin C (Madiha et al., 2024). The fruit is considered as a promising commodity for functional food product.

The fruit has been reported previously processed into various derivative products, including jams, pickles, jellies, vinegar, wine, and beverages (Prasad et al., 2021). Eaten raw or served as traditional dishes such as *bilimbir daal* or bilimbi soup are very common in Sri Lanka and Bangladesh (Bhuiyan et al., 2022; Waisundara, 2020). The fruit also fermented and utilised as traditional seasoning locally known as *asam sunti* in Aceh Province, Indonesia (Istiqamah et al., 2019). Anuar and Salleh (2019) reported research of bilimbi fruit with focus on preserving the fruit through processing techniques such as jam production. The utilisation of bilimbi fruit for beverages has also been reported in previous studies, e.g., bilimbi fruit tea (Juanda et al., 2022), black tea added with bilimbi fruit extract (Anggraini et al., 2016), bilimbi fruit wine (Caoli et al., 2017), and bilimbi fruit juice (Astillo, 2022). The bilimbi juice can also be used as natural acid coagulant for tofu production (Sitanggang et al., 2020). These developments highlight the growing potential of bilimbi fruit in the food industry, particularly as a health-oriented and consumer goods product.

Bilimbi fruit in Indonesia predominantly used as flavouring agent in local cuisine and is seldom consumed raw. Unlike other sour-source flavour such as tamarind, pineapple, and citrus, bilimbi fruit has limited attention in terms of postharvest research and derivative product development. The high moisture content of bilimbi fruit (>80%) make it highly perishable and typically has a shelf life of less than 24 h after harvest (Alhassan & Ahmed, 2017). Product diversification through postharvest processing, such as drying, is essential to extend utilisation and promote broader consumption.

The drying process not only improves product stability but also enables the availability of product all year long. However, the drying process can impact product quality by causing nutritional and physicochemical alteration. Therefore, optimised drying process is critical to balance food safety and product quality. In order to optimise the drying process, the fundamental data such as moisture sorption isotherms (MSI) and thermal properties of the fruit are necessary. MSI are fundamental in designing drying process and determining suitable packaging and storage conditions for dried products (Hssaini et al., 2022a). The MSI described the relationship between equilibrium moisture content and water activity at a constant temperature are unique to each product, depending on its composition and structure (Li & Ramaswamy, 2025). Accurate MSI data enable manufacturers to control drying endpoints, minimise deterioration, and ensure product safety. MSI behaviour has been studied previously for food products, e.g., muntries, finger lime, cabya, butterfly-pea flower, cassava flour, fig, yacon, cheese-puri, and corn starch jelly candy (Bernstein and Noreña, 2013; Efendi, 2024; Hawa et al., 2020, 2021; Hssaini et al., 2022; Michalski et al., 2025; Thanuja & Ravindra, 2014).

The present study aims to determine the MSI of bilimbi fruit at three temperatures (25, 35, 45°C) using standard gravimetric method. Additionally, the experimental data are modelled using established sorption equations, and the thermodynamics properties, including net isosteric heat of sorption and the critical water activity boundaries during adsorption and desorption, are evaluated.

METHODS

Sample Preparation

The fresh bilimbi fruits as raw materials were obtained from local farmers in Malang, East Java Province, Indonesia. The fruits were collected at the green edible maturity stage with approximately 95% (wb) of moisture content depict in Figure 1. The fruit then cleaned from excessive peduncles and dust then sliced with sharp knife. A single fruit of bilimbi has approximately 6 cm in length and then sliced into eight parts with a thickness of 3 mm each. The sample then grouped into desorption and adsorption sample. For both group of samples, the sliced fruit dehydrated using laboratory hot air dryer (Memmert UFE550, Memmert GmbH, made in Germany) at 50°C for 48 h as adsorption and at 50°C for 12 h as desorption. Five saturated salt solutions (KOH, MgCl2, CaCl2, NaCl, and KCl) were utilised to obtain water activity values ranging from 0.063 to 0.843, as presented in Table 1.

Figure 1. The green edible maturity stage of bilimbi

Table 1
The selected salt used for preparing salt solutions and their corresponding water activities (a_w)

Saturated Salt Solution	a_w (25°)	a_w (35°)	a_w (45°)
KOH	0.082	0.074	0.063
$MgCl_2$	0.328	0.324	0.311
$CaCl_2$	0.640	0.625	0.571
NaCl	0.754	0.752	0.745
KCl	0.843	0.826	0.817

*Source: Bell & Labuza (2000); Rizvi (2005)

Moisture Sorption Isotherm Determination

Moisture sorption isotherms analysis of bilimbi using the gravimetric static method refers to research conducted by Hawa et al. (2020) at three subjected temperatures (25±2ºC, 35±2ºC, and 45±2ºC). The experimental procedure includes fifteen hermetic jars of 350 ml for each sample. Triplicate bilimbi samples for both adsorption and desorption experiments. Two cups were inserted into the hermetic jar. The first cup was plastic with 20 ml of salt solution, and the second cup was an aluminium foil cup filled with a bilimbi sample (1±0.1 g). The identical process is applied to adsorption and desorption. Each sample was placed in a hermetic jar alongside the saturated salt solution. Subsequently, the hermetic jars were placed at constant temperatures (25, 35, and 45 °C) in the incubator (Memmert E07086, Memmert GmbH, Germany). The incubator was previously allowed to be run empty for 2 hours to enable it to stabilise at the target temperature (25±2ºC, 35±2ºC, and 45±2ºC) to maintain a constant relative humidity corresponding to a constant water activity (aw) for respective temperatures (Hawa et al., 2020). Figure 2 illustrates for collecting

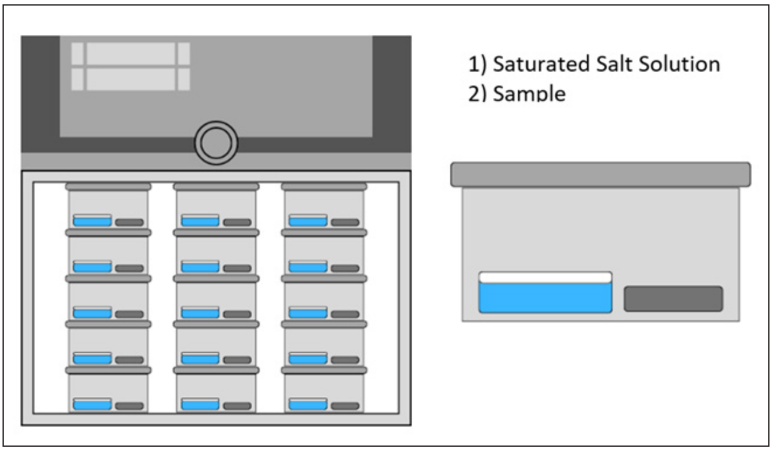


Figure 2. The illustration of hermetic jars placed in the incubator

moisture sorption on bilimbi incubation. The samples were weighed at the sixth hour and subsequently every 24 hours using a digital balance with ±0.001 g of accuracy. The experiment was stopped until the mass remained constant if there is a difference of less than 2% in three consecutive weight measurements. To determine the equilibrium moisture content (EMC), the samples were dried at 105°C for 4 hours.

Mathematical Modelling of Sorption Isotherms

A semi-empirical sorption model was used to predict the equilibrium moisture content of bilimbi (Oduola et al., 2022). The research used five models to predict moisture sorption phenomena, namely GAB, BET, Peleg, Chung-pfost, and Halsey. The summarised of five models showed in Table 2 were fitted using Microsoft Excel 365 for Windows. Where a_w is the water activity, a, b, n, K, and C are dimensionless constants, and *Mo* is the monolayer water content in wet basis.

Each model was evaluated using statistical analysis. It is essential to recognise the parameters of model accuracy in order to identify the suitability of the model used by established standards. Statistical analysis was used to determine water activity, on changes in equilibrium moisture content. To evaluate the model performance, the coefficient of determination (R^2), chi square (χ^2), mean relative percent error (P), and root mean square error (*RMSE*) between the experimental and the predicted data were used. The value of R^2 is the main criterion for initial model selection, where χ^2, RMSE, and P are the second, the third, and the supplementary criterion, respectively (Hawa et al., 2021; Hawa et al., 2021; Hawa et al., 2020).

Table 2
The mathematical models for fit the sorption isotherms of bilimbi

Semi-empirical Sorption Model	**Equation**
GAB	$EMC = \frac{M_o C K a_w}{(1 - K a_w)(1 - K a_w + C K a_w)}$
BET	$EMC = \frac{M_o C a_w}{(1 - a_w)(1 + (C - 1) a_w}$
Peleg	$EMC = a {a_w}^b + C {a_w}^n$
Chung-pfost	$EMC = a - b\, ln[-(T + c)\, ln(a_w)]$
Halsey	$EMC = \left(-\frac{C}{ln\, a_w}\right)^{1/n}$

*Source: Andrade & Hensel (2013)

$$R^2 = \frac{\left(\sum_{i=1}^{N}\left(EMC_{exp} - \overline{EMC}_{exp}\right)\left(EMC_{pre} - \overline{EMC}_{pre}\right)\right)^2}{\sum_{i=1}^{N}\left(EMC_{exp} - \overline{EMC}_{exp}\right)^2 \sum_{i}^{N}\left(EMC_{pre} - \overline{EMC}_{pre}\right)^2} \quad [1]$$

$$\chi^2 = \frac{\sum_{i}^{N}\left(EMC_{exp} - EMC_{pre}\right)^2}{N-n} \quad [2]$$

$$P = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{EMC_{exp} - EMC_{pre}}{EMC_{exp}}\right| \quad [3]$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(EMC_{exp} - EMC_{pre}\right)^2\right]^{\frac{1}{2}} \quad [4]$$

Thermodynamics Properties Determination

Determination of the Sorption Heat

The differential enthalpy commonly termed isosteric heat of sorption Q_{st} (kJ mol^{-1}) and defined as the sum of the net isosteric heat of adsorption (q_{st}) and the latent heat of condensation of pure water (Q_c) at the average experimental temperature. To determine the isosteric heat os sorption, moisture sorption data obtained from the best fitting isotherm model at three distinct temperatures were employed. The values were calculated through the linearised form of the Clausius–Clapeyron equation as below (Hssaini et al., 2022; Sahu et al., 2018), where a_w is the water activity, T (K) is the temperature, q_{st} is the net isosteric heat of sorption, and R is the ideal gas constant (8.314×10^3 kJ mol^{-1} K^{-1}).

$$q_{st} = -R\left[\frac{d[\ln a_w]}{d\left(\frac{1}{T}\right)}\right]_M \quad [5]$$

To estimate the net isosteric heat of sorption (q_{st}), a specific moisture content (M) was assumed. The corresponding water activity (a_w) values were predicted using the best-fitting sorption isotherm model. A linear relationship between $\ln a_w$ and $1/T$ was established, and the slope of the resulting plot was used to calculate the value of q_{st}. In this analysis, the assumed moisture content was set to the monolayer moisture content (Mm), as determined from the selected sorption model. The required a_w values for the given moisture contents were computed using Microsoft Excel 365. The value of the isosteric heat of sorption (Q_{st}) was determined from the following relationship, where Q_c is the heat of condensation of pure water (43.65 kJ mol^{-1}) at the mean temperature (308.15 K) used in this study.

$$Q_{st} = q_{st} + Q_c \tag{6}$$

Determination of the Sorption Entropy

Sorption entropy was determined by applying equation to the sorption data predicted by the best-fitting sorption model as below (Hssaini et al., 2022; Sahu et al., 2018), where ΔS is the entropy (kJ mol^{-1}). The value ΔS was computed from the intercept ($\Delta S/R$) value of the plot between $ln\ a_w$ and $1/T$ for definite values of moisture content.

$$-ln\ a_w = \frac{Q_{st}}{RT} - \frac{\Delta S}{R} \tag{7}$$

Determination of Critical Water Boundary

Primary Bound Water

The critical limit of primary bound water was calculated using the BET (Brunauer-Emmett-Teller) equation by plotting a graph of a_w data against [$a_w/(1-a_w)\ X_e$] (Jamaluddin et al., 2014).

$$\frac{a_w}{(1-a_w)\ Xe} = \left(\frac{1}{X_m\ .C}\right) + \left(\frac{a_w\,(C-1}{X_m\ .C}\right) \tag{8}$$

Secondary Bound Water

Logarithmic analysis can be used to determine the limit of secondary bound water. $Log(1-a_w)$ data plotted against X_e results in a straight line that splits into two. The coordinates expressed as $Log(1-a_w)$ which is the relationship between $Log(1-a_w)$ and water will produce two straight line curves. The first line represents the position of the secondary bound water, while the second line represents the tertiary bound line. The intersection of the two lines indicates the maximum amount of secondary bound water capacity (Jamaluddin et al., 2014).

$$log\ (1 - a_w) = b\ (X_e) + a \tag{9}$$

Tertiary Bound Water

The tertiary bound water was determined using a second-order polynomial model, with the value of tertiary bound water limited to a_w values greater than the fraction of secondary bound water (Jamaluddin et al., 2014).

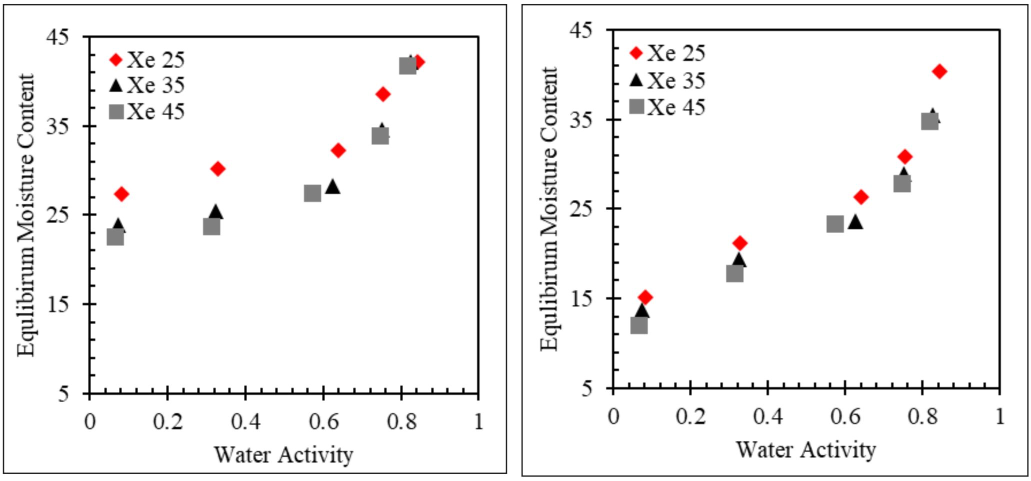
$$y = ax^2 + bx + c \tag{10}$$

RESULTS AND DISCUSSION

Equilibrium Moisture Content of Dried Bilimbi

The equilibrium moisture content of samples during adsorption and desorption at temperatures of 25°C , 35°C , and 45°C are shown in Figure 3. The equilibrium moisture content of the adsorption samples rises with elevated relative humidity at a constant temperature and diminishes with reduced relative humidity (Figure 3) (Yadav & Mishra, 2023). At elevated temperatures, the kinetic energy of water molecules will increase, hence diminishing the intermolecular forces of attraction among them. As temperature increases, the water activity of the saturated salt solution and the equilibrium moisture content decrease (Arslan-Tontul, 2020).

Similar to the adsorption samples, the desorption samples exhibited a linear correlation between equilibrium water content and water activity. As illustrated in Figure 3, the equilibrium moisture content of bilimbi increased as water activity at a constant temperature condition (Fadimu et al., 2019). At a constant water activity, the desorption equilibrium moisture content was observed to be lower than the adsorption equilibrium moisture content. This illustrates the reversed phenomenon of hysteresis frequently observed. The phenomenon of capillary condensation results in a swift escalation of the adsorption sample prior to the attainment of pressure equilibrium. This process transpires when water vapor persistently adsorbs in many layers within porous solids until the pore space is saturated with water. This anomalous phenomenon is explained in the study by Shen et al. (2023) which references to the hypothesis proposed by Broekhoff and de Boer in 1973, asserting that the filling of open holes results from an unstable adsorption layer intricately



(a)

(b)

Figure 3. Equilibrium moisture content of bilimbi: (a) adsorption sample, (b) desorption sample

linked to the pore radius. The desorption pressure is inferior to the adsorption pressure. The configuration of the closed space is a primary element influencing the elevation of adsorption hysteresis beyond desorption hysteresis. The anomalous behavior observed in adsorption samples is affected by the development of multimolecular adsorption layers until the constricted regions of the pores are obstructed, resulting in the creation of a meniscus that induces capillary condensation (Broekhoff & de Boer, 1967).

Mathematical Modelling of the Moisture Sorption Isotherm

The fittest model to represent moisture sorption isotherms of bilimbi was chosen based on the predicted value that most closely aligns with experimental value. In order to evaluate the model performance, the statistical parameters, i.e., R^2, χ^2, RMSE, and P values. Table 3 summarises the statistical parameters based on fitting results of experimental data to the selected models used. Based on the main criterion, it can be seen that BET model consistently gives the highest R^2 with lowest χ^2 and RMSE values in all tested temperature. The BET model also provides the same performance in both adsorption and desorption samples within tested water activity range (0.063 to 0.843).

Table 3
Moisture sorption statistical performance

Model	T (°C)	Adsorption				Desorption			
		R^2	χ^2	RMSE	P	R^2	χ^2	RMSE	P
GAB	25	0.9170	0.0338	0.1163	28.8	0.9401	0.0093	0.0609	25.9
	35	0.8645	0.0247	0.0993	28.2	0.9533	0.0077	0.0557	25.5
	45	0.8899	0.0222	0.0942	24.1	0.9710	0.0059	0.0486	23.9
BET	25	0.9768	0.0290	0.1318	25.8	0.9842	0.0078	0.0685	21.5
	35	0.9945	0.0152	0.0953	19.9	0.9843	0.0056	0.0578	19.7
	45	0.9984	0.0128	0.0875	21.2	0.9729	0.0046	0.0524	21.3
Peleg	25	0.8460	0.0014	0.0292	7.8	0.9075	0.0022	0.0363	12.5
	35	0.7752	0.0030	0.0426	12.2	0.9188	0.0015	0.0298	11.5
	45	0.7900	0.0032	0.0439	13.7	0.9410	0.0012	0.0270	12.1
Chung-pfost	25	0.9501	0.0007	0.0171	4.1	0.9702	0.0011	0.0208	6.5
	35	0.9040	0.0021	0.0288	8.5	0.9759	0.0007	0.0164	5.5
	45	0.9190	0.0020	0.0281	9.2	0.9851	0.0005	0.0135	5.1
Halsey	25	0.9788	0.0450	0.1643	47.5	0.9873	0.0153	0.0957	39.9
	35	0.9927	0.0273	0.1281	40.0	0.9877	0.0117	0.0837	38.1
	45	0.9971	0.0248	0.1221	40.3	0.9780	0.0103	0.0786	38.0

The Brunauer-Emmett-Teller (BET) model is the foundational mathematical model used to describe the relationship between equilibrium moisture content and water activity in food products, including bilimbi. It is especially important for understanding and predicting how food interact with moisture during storage, processing, and packaging. The BET model is based on the theory of multilayer adsorption, where water molecules first form a monolayer on the food surface and then additional layers at higher water activities. The BET model also allows the determination of two key parameters, i.e., the monolayer moisture content (M_o) and BET energy constant (C). The monolayer moisture content (M_o) represents the amount of water strongly bound to the food surface (Staudt et al., 2013). Below the M_o value, the food is most stable with minimal chemical and microbial changes. BET constant (C) reflects the energy of adsorption in the first layer compared to subsequent layers. The M_o value from BET model is used to determine optimal moisture levels for storage stability. Foods stored at or below this moisture content are less prone to spoilage and quality loss (Abdullah et al., 2020). Based on the results, it can be seen than dried bilimbi fruit will safe at below 0.087 (d.b.) if stored at room temperature (approx. 25-35°C).

The BET model is universally accepted mathematical models to describe the sorption behaviour of various fruit, e.g. banana, mango, and pineapple (Talla et al., 2005), apple with PEF treatment (Castagnini et al., 2020), green and red peppers (Kaymak-Ertekin & Sultanoglu, 2001), and green chilli (Getahun et al., 2020). In addition, (Andrade & Hensel, 2013) mentioned that BET model also found to suitable for dried tomato, apple, and blueberry.

Hysteresis Curve of Moisture Sorption Isotherm

The hysteresis curve observed for dried bilimbi at all tested temperatures depicted in Figure 4. It was a convincing confirmation that the experimental adsorption and desorption data display a clear sigmoidal trend. The curve corresponding to a Type II moisture sorption isotherm typically associated with multilayer adsorption in food system (Al-Muhtaseb et al., 2002). The sigmoidal profile characteristics reflects multilayer adsorption driven by Raoults's law, capillary effect, and surface moisture interactions (Labuza & Altunakar, 2020). The results also showed that the sigmoidal pattern is clearly observed across all temperatures, confirming that the moisture binding mechanism conforms to multilayer formation typical of high-moisture fruit matrices. The hysteresis loop in the bilimbi isotherms also reveals two distinct regions of equilibrium moisture variation, i.e., at water activities of approximately 0.2–0.4 and 0.6–0.7, which correspond to multilayer adsorption and progressive pore filling. These features mirror trends reported previously for other starchy and high-carbohydrate foods.

Hysteresis is a well-documented phenomenon in food and fruit moisture sorption isotherms, where the desorption curve (drying) lies above the adsorption curve (rehydration) at the same water activity. This means that, for a given water activity, the equilibrium moisture content is higher during desorption than during adsorption. This pattern is observed in a wide range of foods, including bananas and tamarind (Pandian et al., 2025; Yan et al.,

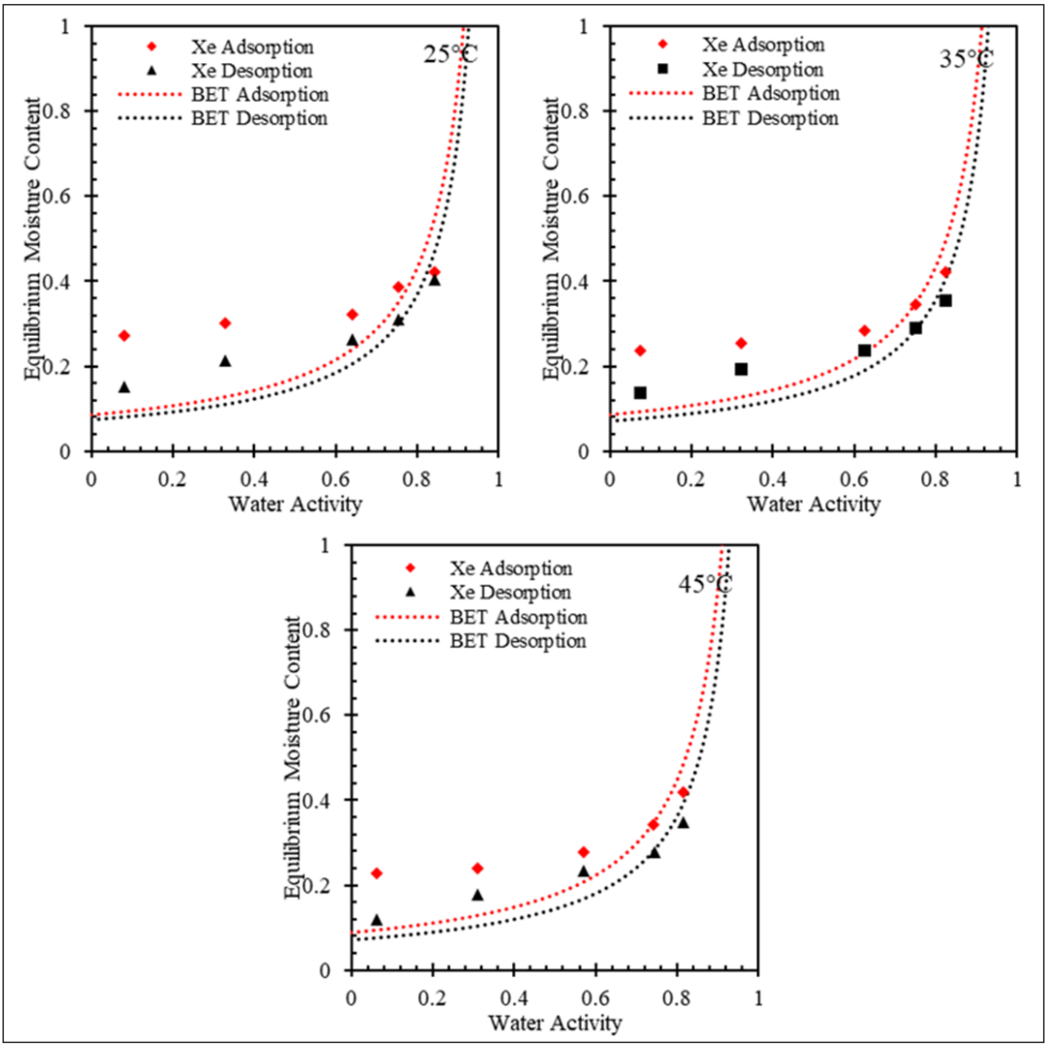


Figure 4. Sorption isotherms of bilimbi at different temperatures fitted with the BET model

2008). The higher desorption curve is attributed to structural and physicochemical changes in the food matrix during drying, such as pore collapse, capillary effects, and strong binding of water in small pores, which make it harder for water to leave during desorption than to enter during adsorption (Fikry et al., 2025). However, the hysteresis magnitude in bilimbi, where adsorption values consistently exceed desorption values, aligns with the pattern noted by (Shen et al., 2023). While the vast majority of studies report the desorption curve above the adsorption curve, crossing or overlap can occur at very high-water activities or under specific conditions as previously reported for whole black peppercorns (Yogendrarajah et al., 2015) and four-finger threadfin (Saniso et al., 2025).

Critical Water Boundary

Figure 5 shows the position of the bound water fraction in the adsorption and desorption samples at the three storage temperatures used. The position of the bound water fraction in bilimbi is influenced by the condition of water activity and equilibrium water content at constant storage temperature conditions. (Thanuja & Ravindra, 2014) stated that the sorption isothermal phenomenon in materials can be divided into three zones based on the observed decrease in equilibrium moisture content. Zone I is primary bound water (a_w 0 - 0.35), Zone II is secondary bound water (a_w 0.35 - 0.80), and Zone III is tertiary bound water (a_w > 0.8).

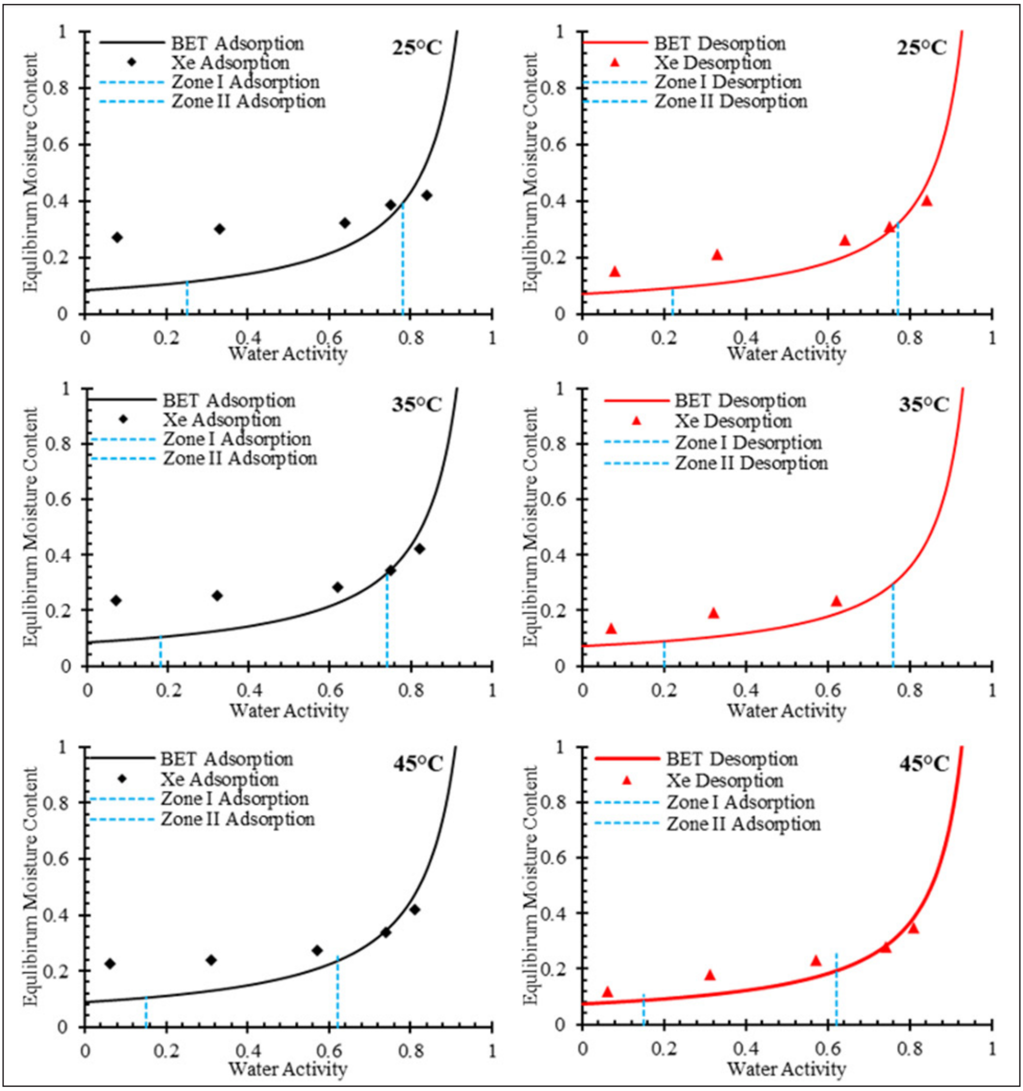


Figure 5. Bound water fraction for adsorption and desorption at different temperatures

Across all temperatures, the bilimbi sorption isotherms show the typical three-zone pattern of a Type II curve. In Zone I ($a_w \approx$ 0-0.2), the equilibrium moisture content remains low and increases only slightly, indicating the presence of strongly bound water associated with hydrophilic sites on the solid matrix. This water is tightly held and cannot be easily removed due to strong interactions with polar constituents. In Zone II ($a_w \approx$ 0.2-0.7), the moisture content increases gradually and almost linearly, corresponding to the formation of multilayer water held by weaker intermolecular forces. This region reflects the adsorption of water beyond the primary sorption sites, and its slope matches the behaviour shown in the graphs. In Zone III ($a_w >$ 0.7), the equilibrium moisture content rises sharply as free or capillary water accumulates within macropores. This rapid increase reflects water that is only weakly bound and is readily available to support microbial growth and enzymatic activity, consistent with the steep curvature observed in the plotted bilimbi adsorption and desorption data. The similar findings have been reported previously on fruit products, e.g., fig (Hssaini et al., 2022) and sweet cherry (Ouaabou et al., 2022).

Isosteric and Net Isosteric Heat

The experimental results for bilimbi showed that the maximum net isosteric heat of sorption reached 96.43 kJ/mol, while the highest isosteric heat reached 140.08 kJ/mol (Figure 6 and 7). The net isosteric heat represents the energy required to evaporate water bound within the food matrix, and in case of bilimbi, the adsorption consistently exhibited higher value than desorption. This trend aligns with (Koua et al., 2012), who reported that, at a constant equilibrium moisture content, the net isosteric heat of desorption generally exceeds that of absorption. It was due to water removal requires greater energy than capillary condensation. A positive net isosteric heat reflects the release of energy during sorption.

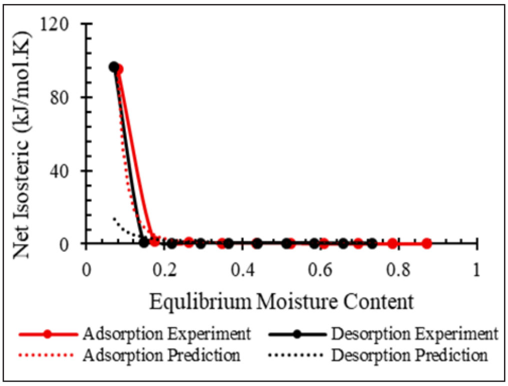


Figure 6. Sorption net isosteric of bilimbi at different moisture content

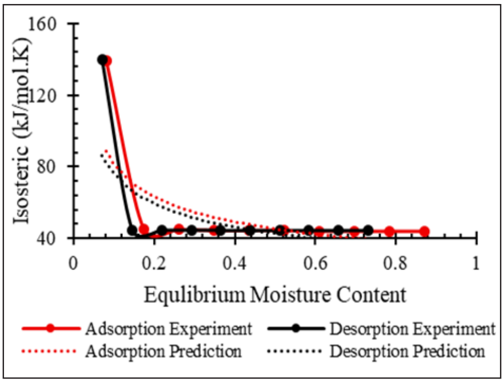


Figure 7. Sorption isosteric of bilimbi at different moisture content

The higher energy demand during adsorption compared with desorption is consistent with the findings of Shen et al. (2023), who associated this difference with the presence of energy barriers during transitions between metastable states in adsorption–desorption processes. (Desgranges & Delhommelle, 2019) further demonstrated that the free energy required to initiate capillary condensation decreases as surface moisture increases.

Isosteric heat provides important insight into liquid–solid interactions during storage. In bilimbi, the isosteric heat is highest at low equilibrium moisture content and decreases as moisture content increases. At low moisture levels, water molecules are strongly bound to hydrophilic components such as carbohydrates and proteins, requiring more energy for evaporation. Conversely, at higher moisture contents, water behaves more like free water, reducing the energy needed for phase change. This pattern is consistent with the results of Barati et al. (2016), who observed that net isosteric heat is greatest at low water content and diminishes as equilibrium moisture content increases due to the shift from tightly bound water to weaker bound or free water.

CONCLUSION

This study successfully characterised the moisture sorption behaviour and thermodynamic properties of Averrhoa bilimbi fruit. Moisture sorption isotherms were significantly affected by temperature and showed typical sigmoidal (Type II) hysteresis behaviour. The BET model provided the most accurate prediction of equilibrium moisture content across the tested temperature range and sorption conditions. Thermodynamic analysis revealed that net isosteric heat and entropy decreased with increasing moisture content, indicating stronger water–solid interactions at lower moisture levels. The identification of critical water activity zones (primary, secondary, and tertiary bound water) contributes to understanding the fruit's moisture retention and stability during drying and storage.

ACKNOWLEDGEMENT

This research received financial support from Universitas Brawijaya, in the framework of Hibah Guru Besar Universitas Brawijaya Fakultas Teknologi Pertanian funding scheme (No. 01213/UN.F1001/B/PT0103.2/2024).

REFERENCES

Abdullah, S., Keoh, S. C., Johar, H. M., Razak, N. A., Shaari, A. R., & Rukunudin, I. H. (2020). Mathematical modelling of moisture sorption isotherms by using BET and GAB models. *IOP Conference Series: Materials Science and Engineering*, *932*(1). https://doi.org/10.1088/1757-899X/932/1/012037

Alhassan, A., & Ahmed, Q. (2016). Averrhoa bilimbi Linn.: A review of its ethnomedicinal uses, phytochemistry, and pharmacology. *Journal of Pharmacy & Bioallied Sciences*, *8*(4), 265. https://doi.org/10.4103/0975-7406.199342

Al-Muhtaseb, A. H., McMinn, W. A. M., & Magee, T. R. A. (2002). Moisture sorption isotherm characteristics of food products: A review. *Food and Bioproducts Processing*, *80*(2), 118–128. https://doi.org/10.1205/09603080252938753

Andrade, S. P. C., & Hensel, O. (2013). Experimental determination and mathematical fitting of sorption isotherms for Lemon Balm (Melissa officinalis L.). *Agricultural Engineering International: CIGR Journal*, *15*(1), 139–145. https://cigrjournal.org/index.php/Ejounral/article/view/2146

Anggraini, T., Febrianti, F., Aisman, & Ismanto, S. D. (2016). Black tea with averrhoa bilimbi L extract: A healthy beverage. *Agriculture and Agricultural Science Procedia*, *9*, 241–252. https://doi.org/10.1016/j.aaspro.2016.02.141

Anuar, N. A., & Salleh, R. M. (2019). Development of fruit jam from Averrhoa bilimbi L. *Journal of Food Processing and Preservation*, *43*(4). https://doi.org/10.1111/jfpp.13904

Arslan-Tontul, S. (2020). Moisture sorption isotherm, isosteric heat, and adsorption surface area of whole chia seeds. *LWT*, *119*, 108859. https://doi.org/10.1016/j.lwt.2019.108859

Astillo, J. D. (2020). Bilimbi fruit (Averrhoabilimbi) juice. *International Journal of Environment, Agriculture and Biotechnology*, *5*(3). https://doi.org/10.22161/ijeab.53.12

Barati, M., Zare, D., & Zomorodian, A. (2016). Moisture sorption isotherms and thermodynamic properties of safflower seed using empirical and neural network models. *Journal of Food Measurement and Characterisation*, *10*(2), 236–246. https://doi.org/10.1007/S11694-015-9298-4

Bernstein, A., & Noreña, C. P. Z. (2013). Study of thermodynamic, structural, and quality properties of Yacon (Smallanthus sonchifolius) during drying. *Food and Bioprocess Technology 2013*, *7*(1), 148–160. https://doi.org/10.1007/s11947-012-1027-y

Bhuiyan, M. H. R., Hossain, M. A., & Yeasmen, N. (2022). Local-traditional foods of Bangladesh: A treasure to be preserved. *International Journal of Gastronomy and Food Science*, *30*. https://doi.org/10.1016/j.ijgfs.2022.100602

Broekhoff, J. C. P., & de Boer, J. H. (1967). Studies on pore systems in catalysts: IX. Calculation of pore distributions from the adsorption branch of nitrogen sorption isotherms in the case of open cylindrical pores A. Fundamental equations. *Journal of Catalysis*, *9*(1), 8–14. https://doi.org/10.1016/0021-9517(67)90174-1

Caoli, M. A., Arenillo, S. A., & Magsino, R. F. (2017). Acceptability of Kamias (Averrhoabilimbi) wine. *Asia Pacific Journal of Multidisciplinary Research*, *5*(2), 85–88.

Castagnini, J. M., Iaccheri, E., Tylewicz, U., Dalla Rosa, M., & Rocculi, P. (2020). Pulsed electric fields effect on mechanical and sorption properties of dried apple tissue. *Innovative Food Science & Emerging Technologies*, *65*, 102442. https://doi.org/10.1016/j.ifset.2020.102442

Desgranges, C., & Delhommelle, J. (2019). Nucleation of Capillary Bridges and Bubbles in Nanoconfined CO2. *Langmuir*, *35*(47), 15401–15409. https://doi.org/10.1021/acs.langmuir.9b01744

Efendi, M. (2024). Influence of glazing type on the drying kinetics and thermal performance of indirect solar dryer for jelly candy. *Renewable Energy*, *231*. https://doi.org/10.1016/j.renene.2024.120950

Fadimu, G. J., Sanni, L. O., Adebowale, A. R. A., Kareem, S. O., Sobukola, O. P., Kajihausa, O. E., Saghir, A., Siwoku, B., Akinsanya, A., & Adenekan, M. K. (2018). Effect of drying methods on the chemical composition, colour, functional and pasting properties of plantain (*Musa Parasidiaca*) Flour. *Hrvatski Časopis Za Prehrambenu Tehnologiju Biotehnologiju I Nutricionizam*, *13*(1–2), 38–43. https://doi.org/10.31895/hcptbn.13.1-2.2

Fikry, M., Al-Ghamdi, S., Alfaifi, B., Ibrahim, M. N., Alqahtani, N., Umar, M., & Assatarakul, K. (2025). Mathematical modelling of sorption isotherms and the thermodynamic properties of vacuum-dried and freeze-dried Barhi dates. *Scientific Reports 2025 15:1*, *15*(1), 19781-. https://doi.org/10.1038/s41598-025-01935-x

Garg, M., Chaudhary, S. K., Kumari, S., & Goyal, A. (2022). Phytochemical, biological and traditional claims on Averrhoa bilimbi: An Overview. *Indian Journal of Pharmaceutical Sciences*, *84*(3), 532–542. https://doi.org/10.36468/pharmaceutical-sciences.947

Getahun, E., Gabbiye, N., Delele, M. A., Fanta, S. W., Gebrehiwot, M. G., & Vanierschot, M. (2020). Effect of maturity on the moisture sorption isotherm of chili pepper (Mareko Fana variety). *Heliyon*, *6*(8), e04608. https://doi.org/10.1016/j.heliyon.2020.e04608

Hawa, L. C., Efendi, M., Ubaidillah, Razak, A. A., & Wibisono, Y. (2021). Moisture sorption isotherm and isosteric heat of butterfly-pea flowers (*Clitoria ternatea*). *IOP Conference Series: Earth and Environmental Science*, *757*(1), 012028. https://doi.org/10.1088/1755-1315/757/1/012028

Hawa, L. C., Efendi, M., Ubaidillah, U., & Yulianingsih, R. (2021). Determination and modelling moisture sorption isotherms of dehydrated butterfly-pea (Clitoria ternatea L.) flower powder. *IOP Conference Series: Earth and Environmental Science*, *924*(1), 012010. https://doi.org/10.1088/1755-1315/924/1/012010

Hawa, L. C., Ubaidillah, U., Damayanti, R., & Hendrawan, Y. (2020). Moisture sorption isotherms of modified cassava flour during drying and storage. *Heat and Mass Transfer/Waerme- Und Stoffuebertragung*, *56*(8), 2389–2396. https://doi.org/10.1007/S00231-020-02866-1

Hssaini, L., Ouaabou, R., Charafi, J., Idlimam, A., Lamharrar, A., Razouk, R., & Hanine, H. (2022). Hygroscopic proprieties of fig (Ficus carica L.): Mathematical modelling of moisture sorption isotherms and isosteric heat kinetics. *South African Journal of Botany*, *145*, 265–274. https://doi.org/10.1016/j.sajb.2020.11.026

Istiqamah, A., Lioe, H. N., & Adawiyah, D. R. (2019). Umami compounds present in low molecular umami fractions of asam sunti – A fermented fruit of Averrhoa bilimbi L. *Food Chemistry*, *270*, 338–343. https://doi.org/10.1016/j.foodchem.2018.06.131

Jamaluddin, J., Molenaar, R., & Tooy, D. (2014). Kajian isotermi sorpsi air dan fraksi air terikat kue pia kacang hijau asal kota Gorontalo [Study on moisture sorption isotherm and bound water fractions of green beans taste of pia cake from Gorontalo]. *Jurnal Ilmu dan Teknologi Pangan*, *2*(1), 27–36.

Juanda, Agustina, R., & Hartuti, S. (2022). Optimisation of sensory characteristics of bilimbi tea drink (Averrhoa Tea). *IOP Conference Series: Earth and Environmental Science*, *1116*(1). https://doi.org/10.1088/1755-1315/1116/1/012066

Kaymak-Ertekin, F., & Sultanoglu, M. (2001). Moisture sorption isotherm characteristics of peppers. *Journal of Food Engineering*, *47*(3), 225–231. https://doi.org/10.1016/S0260-8774(00)00120-5

Koua, B. K., Koffi, P. M. E., Gbaha, P., & Toure, S. (2012). Thermodynamic analysis of sorption isotherms of cassava (Manihot esculenta). *Journal of Food Science and Technology*, *51*(9), 1711. https://doi.org/10.1007/S13197-012-0687-y

Labuza, T. P., & Altunakar, B. (2020). Water activity prediction and moisture sorption isotherms. *Water Activity in Foods: Fundamentals and Applications*, 161–205. https://doi.org/10.1002/9781118765982.ch7

Li, H., & Ramaswamy, H. S. (2025). Influence of osmotic dehydration conditions and finish air drying on the adsorption isotherms of cylindrical apple slices. *Drying Technology*, *43*(1–2), 321–330. https://doi.org/10.1080/07373937.2024.2440803

Michalski, P., Nur-A-Tomal, M. S., Crawford, S., Rudman, M., & van 't Hag, L. (2025). Advancement in fruit drying through the analysis of moisture sorption isotherms: processing effects on Australian native fruits in comparison to apple. *Journal of Food Engineering*, *395*. https://doi.org/10.1016/j.jfoodeng.2025.112526

Mokhtar, S. I., & Abd Aziz, N. A. (2016). Antimicrobial Properties of Averrhoa bilimbi extracts at different maturity stages. *Journal of Medical Microbiology & Diagnosis*, *5*(3). https://doi.org/10.4172/2161-0703.1000233

Oduola, A. A., Luthra, K., & Atungulu, G. G. (2022). Determination of moisture sorption isotherms of industrial hemp (Cannabis sativa L.) flower and leaf composite powders. *Industrial Crops and Products*, *186*, 115201. https://doi.org/10.1016/j.indcrop.2022.115201

Ouaabou, R., Ennahli, S., Hssaini, L., Nabil, B., Idlimam, A., Lamharrar, A., Mahrouz, M., & Hanine, H. (2022). Moisture sorption isotherms of sweet cherry (*Prunus Avium* L.): Comparative study of kinetics and thermodynamic modelling of five varieties. *International Journal of Food Science*, *2022*(1), 6786590. https://doi.org/10.1155/2022/6786590

Pandian, N. K. S., Naveenkumar, M., Arulkumar, M., Kamaleeswari, K., Ramkumar, R., Karuppuchamy, V., Kishore, S. G., & Pandiselvam, R. (2025). Adsorption and desorption kinetics of deseeded tamarind (*Tamarindus indica* L.) fruit and its modelling approach. *Journal of Food Process Engineering*, *48*(4), e70092. https://doi.org/10.1111/jfpe.70092

Prasad, S. C., K, V. K., & Reghu, R. (2021). international journal of research in pharmaceutical sciences consumption of bilimbi cause acute kidney injury production and hosted by. *Int. J. Res. Pharm. Sci*, *2021*(1), 653–655. https://doi.org/10.26452/ijrps.v12i1.4146

Sahu, S. N., Tiwari, A., Sahu, J. K., Naik, S. N., Baitharu, I., & Kariali, E. (2018). Moisture sorption isotherms and thermodynamic properties of sorbed water of chironji (Buchanania lanzan Spreng.) kernels at different storage conditions. *Journal of Food Measurement and Characterisation*, *12*(4), 2626–2635. https://doi.org/10.1007/S11694-018-9880-7

Saniso, E., Hayibaka, M., Chaidana, H., & Techo, J. (2025). Moisture sorption isotherm and isosteric heat of sorption of four-finger threadfin (Eleutheronema tetradactylum). *Food Biophysics*, *20*(2). https://doi.org/10.1007/S11483-025-09961-y

Sarker, M. A. M., & Chowdhury, A. Y. S. F. U. A. (2024). Estimation of total phenolic content and antioxidant activity of methanolic extracts of leaf, bark and fruit of Averrhoa bilimbi Linn. *Bangladesh Medical Research Council Bulletin*, *50*(1), 10–14. https://doi.org/10.3329/bmrcb.v50i1.68855

Shen, J. F., Wu, C. M., Song, J., Yu, J. J., & Li, Y. R. (2023). Adsorption and capillary condensation transitions on nanostructures: Mechanisms of atomic evolution and meniscus growth. *International Communications in Heat and Mass Transfer*, *148*, 107064. https://doi.org/10.1016/j.icheatmasstransfer.2023.107064

Sitanggang, A. B., Alexander, R., & Budijanto, S. (2020). The utilisation of bilimbi (Averrhoa bilimbi) and lime (Citrus aurantifolia) juices as natural acid coagulants for tofu production. *Journal of Food Science and Technology*, *57*(12), 4660–4670. https://doi.org/10.1007/S13197-020-04503-5

Staudt, P. B., Kechinski, C. P., Tessaro, I. C., Marczak, L. D. F., De, R., & Cardozo, N. S. M. (2013). A new method for predicting sorption isotherms at different temperatures using the BET model. *Journal of Food Engineering*, *114*(1), 139–145. https://doi.org/10.1016/j.jfoodeng.2012.07.016

Talla, A., Jannot, Y., Nkeng, G. E., & Puiggali, J. R. (2005). Experimental determination and modelling of sorption isotherms of tropical fruits: Banana, mango, and pineapple. *Drying Technology*, *23*(7), 1477–1498. https://doi.org/10.1081/DRT-200063530

Thanuja, D., & Ravindra, M. R. (2014). Thermodynamic analysis of moisture sorption characteristics of cheese-puri mix. *Journal of Food Processing and Preservation*, *38*(1), 420–429. https://doi.org/10.1111/j.1745-4549.2012.00790.x

Waisundara, V. Y. (2020). Traditional functional food of Sri Lanka and their health significance. *Nutritional and Health Aspects of Food in South Asian Countries*, 143–158. https://doi.org/10.1016/B978-0-12-820011-7.00020-4

Yadav, S., & Mishra, S. (2023). Moisture sorption isotherms and storage study of spray-dried probiotic finger millet milk powder. *Journal of Stored Products Research*, *102*. https://doi.org/10.1016/j.jspr.2023.102128

Yan, Z., Sousa-Gallagher, M. J., & Oliveira, F. A. R. (2008). Sorption isotherms and moisture sorption hysteresis of intermediate moisture content banana. *Journal of Food Engineering*, *86*(3), 342–348. https://doi.org/10.1016/j.jfoodeng.2007.10.009

Yogendrarajah, P., Samapundo, S., Devlieghere, F., De Saeger, S., & De Meulenaer, B. (2015). Moisture sorption isotherms and thermodynamic properties of whole black peppercorns (Piper nigrum L.). *LWT - Food Science and Technology*, *64*(1), 177–188. https://doi.org/10.1016/j.lwt.2015.05.045

Yusoff, I. M., Azelee, N. I. W., Chua, L. S., & Mustafa, R. R. (2024). A comparison of phytoconstituent and functional loaded low moisture food from Averrhoa bilimbi using freeze drying and oven drying methods. *Journal of Food Measurement and Characterisation*, *18*(9), 7468–7479. https://doi.org/10.1007/S11694-024-02741-1