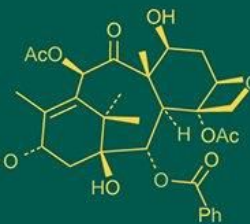
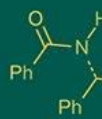


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Optimizing storage conditions for Bael (*Aegle marmelos*) powder through EMC modelling

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Abstract

This study investigates the moisture sorption isotherms of Bael powder at varying relative humidity (RH) levels (20%, 50%, 75%, and 95%) and temperatures (25 °C, 30 °C, and 35 °C). Equilibrium moisture content (EMC) was determined using the gravimetric static method, and the resulting data were fitted to four isotherm models: Anderson, Guggenheim–Anderson–de Boer (GAB), Oswin, and Brunauer–Emmett–Teller (BET). The accuracy of the models was evaluated using the coefficient of determination (R^2) and reduced chi-sqr (χ^2). It was found that GAB model fits best describing equilibrium moisture content and water activity (EMC_{aw}) relationships for Bael powder. The study provides insights into the hygroscopic nature of Bael powder, essential for optimizing its storage conditions and extending its shelf life.

Keywords: Bael powder, sorption isotherm, EMC models, shelf-life

Introduction

Bael (*Aegle marmelos*), an indigenous fruit in the Indian subcontinent, is valued for its medicinal properties and has gained importance in food industries due to its high nutritional content (Mali *et al.*, 2020) [10]. The powder form of Bael is widely used in the formulation of health drinks, functional foods, and nutraceuticals (Anadani *et al.*, 2023) [12]. However, Bael powder's hygroscopic nature makes it susceptible to moisture absorption during storage, which can lead to deterioration in quality (Bag *et al.*, 2009) [4].

Moisture sorption isotherms describe the relationship between the equilibrium moisture content (EMC) of a material and the surrounding relative humidity at a constant temperature (Ocieczek and Zieba, 2020) [13]. This is crucial for understanding and predicting the drying behaviour, storage conditions, and shelf-life of food powders (Sagar and Kumar, 2014) [17]. Studying the sorption behaviour of Bael powder under different environmental conditions is important for improving its commercial viability.

Various mathematical models, such as Anderson, Guggenheim–Anderson–de-Boer (GAB), Brunauer–Emmett–Teller (BET), and Oswin, are commonly used to describe the sorption characteristics of food materials. These models help in identifying the moisture content at which Bael powder remains stable and guide the selection of proper packaging and storage conditions (Stepien *et al.*, 2020) [21].

This study aimed to evaluate the sorption isotherms of Bael powder at different temperatures and RH levels using these four models to better understand its adsorption behaviour for selection of proper environmental conditions for packaging and storage.

Materials and Methods

Raw Material Preparation

Fully ripened Bael fruits (*Aegle marmelos*) were procured from the local market at Pusa, Bihar, India. The fruits were washed thoroughly, and the hard outer shell was manually removed. The inside pulp mixture including gummy seeds was mixed with an equal weight of water (1:1 w/w). This mixture was then passed through a 20-mesh nylon sieve to separate the seeds and fibers. The filtered pulp was collected in sterile plastic containers and immediately stored in a deep freezer for subsequent experiments.

For the preparation of Bael pulp powder, the pulp was dried using a hot air tray dryer. One kilogram of pulp was spread evenly in a thin layer on the drying trays and dried at 65 °C for

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18 ± 2 hours. After drying, the pulp was collected, placed in a desiccator, and then ground using a mixer-grinder. The resulting powder was sieved through a 500 µm stainless steel sieve to ensure uniform particle size. Moisture contents of the fresh and dried pulp were determined using standard AOAC (1990) method. The fresh Bael pulp had a moisture content of 64.51% (wet basis) and the tray-dried Bael powder had a moisture content of 6.93% (wet basis) which was used for subsequent sorption studies.

Experimental method procedure adopted by Iglesias and Chirife (1982) [8] was followed for deriving desorption isotherms of Bael powder at 25, 30, and 35 °C. Approximately 15 g of Bael powder samples were placed in sterilized glass weighing bottles and stored in four partially vacuumed desiccators, each containing different saturated salt solutions (Potassium acetate, Magnesium nitrate, Sodium chloride, Potassium nitrate) (Plate 1). These salt solutions maintained relative humidity (RH) levels of 20, 50, 75 and 95%, as per Young (1967) [23], Greenspan (1977) [7], and Palipane and Driscoll (1992) [14]. To achieve partial vacuum, a vacuum pump was used to remove air from the desiccators (Plate 2).



Plate 1: Desiccators kept in BOD incubator



Plate 2: Bael powder kept in partially vacuumed desiccators

The desiccators were incubated in a thermostatically controlled incubator set at 25 °C. The weight of the samples was recorded at two-days interval until equilibrium moisture content (EMC) was attained, indicated by three consecutive weight measurements showing a difference of less than 0.001 g. The equilibrium period lasted approximately 2–3 weeks depending on the temperature and nature of the

samples. All experiments were conducted in triplicate, and average EMC values were reported. EMC determination was performed using a vacuum oven at 70±1 °C under a pressure of less than 100 mm Hg for 24 hours (AOAC, 1990). The same procedure was repeated for sorption studies at 30 °C and 35 °C by adjusting the incubator temperature accordingly. To prevent mold growth at RH levels above 75%, 5 ml of toluene was placed in the respective desiccators (Labuza, 1984) [12]. Upon reaching equilibrium, the water activity (a_w) of the Bael samples was equal to the RH (as a fraction) inside the desiccators.

Monolayer Moisture Content

The monolayer moisture content is a critical parameter indicating the maximum moisture level at which the product remains most stable. This parameter is essential for determining the surface potential of sorbed moisture in food. It serves as a reliable lower limit for moisture in food products. The monolayer moisture values (X_m) were obtained using the GAB model, as shown in Table 2.

Sorption data analysis

Four sorption models- Anderson, GAB, Oswin, and BET, were employed to fit the experimental data. The model parameters were determined using standard regression techniques with Origin 7.5 software.

Table 1: Desorption models used for fitting the experimental data

Sl no	Model	Equation
1	Anderson,	$X_e = \frac{A B C a_w}{1 + (B-2) C a_w + (1-B) C^2 a_w}$
2	GAB	$X = \frac{X_m C K a_w}{[(1 - K a_w)(1 - K a_w + C K a_w)]}$
3	Oswin,	$X_e = A \left(\frac{a_w}{1 - a_w} \right)^B$
4	BET	$X = \frac{X_m C a_w}{[(1 - a_w)(1 - a_w + C a_w)]}$

Model validation

The suitability of the sorption models in predicting the sorption behavior of Bael powder was evaluated based on the coefficient of determination (R^2), reduced chi-square (χ^2), and residual plots. The residuals were plotted against the predicted EMC values, and the model was considered valid if the residuals were randomly distributed around zero with no systematic patterns. If the residual plot exhibited a distinct pattern, the model was deemed unacceptable.

Results and Discussion

The adsorption isotherms of Bael powder are presented in Fig 1. At 25, 30 and 35 °C. The adsorption isotherms of Bael powder dried at 65 °C were evaluated at three different temperatures (25 °C, 30 °C, and 35 °C), showing a characteristic Type II sigmoidal curve. The equilibrium moisture content (EMC) increased progressively with rising equilibrium relative humidity (ERH) across all temperatures. Similar findings were reported by Bag *et al.* (2009) [4] for different temperature levels and ERH conditions for Bael powder. However, at a constant water activity, EMC exhibited an inverse relationship with temperature, decreasing as temperature rose. This phenomenon can be explained by the heightened kinetic energy of water molecules at higher temperatures, which

reduces water absorption for a given ERH (Martins *et al.*, 2015) ^[11].

The isotherm behaviour is delineated into three regions:

- Region I (ERH: 20%–50%): A zone of minimal moisture uptake, indicating weak interaction between water and the material.
- Region II (ERH: 50%–80%): Displays a linear, steady increase in EMC, implying stronger interactions and

potential for multilayer moisture adsorption.

- Region III (ERH: 80%–100%): A region of accelerated moisture absorption, suggesting water condensation in capillaries or other structural changes in the material.

Results are at par with Gichau *et al.*, (2020) ^[6] Patindol and Norio, (2022) ^[15] and Ociecek and Zieba, (2020) ^[13].

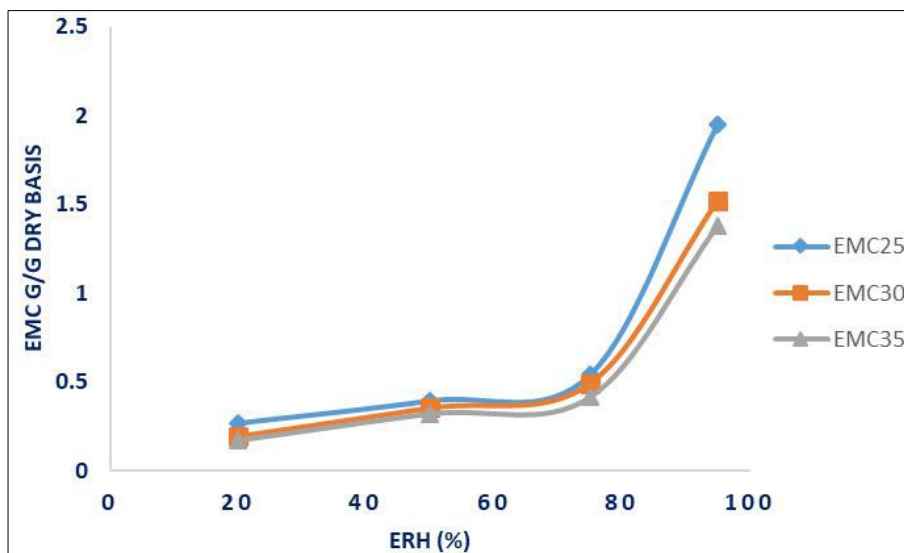


Fig 1: Sorption isotherms of Bael powder

Fitting of Sorption Models

Four sorption models were applied to fit the experimental data for Bael powder dried at 65 °C. Table 2 presents the model constants, coefficient of determination (R^2), and reduced chi-square (χ^2) values at different temperatures (25 °C, 30 °C, and 35 °C). Among the models tested, the GAB model demonstrated the best fit for the adsorption data of Bael powder across all temperatures, as indicated by the consistently high R^2 values and low χ^2 values. This suggests that the GAB model accurately captures the moisture adsorption characteristics of Bael powder at the tested

conditions. Bag *et al.*, (2009) ^[4] suggested Plege as best fitted model for sorption isotherm at higher temperatures for Bael powder. Baptestini *et al.*, (2020) ^[5] studied moisture sorption in soursop fruit powder and found GAB model as best fit for desorption isotherm. Shrivastava (1998) ^[20] found the GAB model to be the best for predicting the EMC of untreated and treated mushrooms within the experimental range of water activity and temperature studied. Therefore, the present findings on Bael powder is in line with other researchers.

Table 2: Constants of different models fitted to the adsorption data of Bael pulp powder

Model	Constants	25°C	30°C	35°C
Anderson's	A	0.30223	0.16498	0.25444
	B	0.97712	1.73695	0.9652
	C	0.91213	0.92676	0.8895
	χ^2 (Reduced Chi-Sqr)	0.07309	0.03966	0.03576
	R^2	0.96027	0.96305	0.96013
GAB	A	13.753	12.642	8.229
	B	0.96068	0.94426	0.95157
	Xm	0.17007	0.15617	0.13183
	χ^2 (Reduced Chi-Sqr)	0.01269	0.00544	0.00702
	R^2	0.99309	0.99492	0.99217
OSWIN	A	0.33893	0.31161	0.26444
	B	0.59132	0.53554	0.55717
	χ^2 (Reduced Chi-Sqr)	0.01482	0.00455	0.00561
	R^2	0.98389	0.99152	0.98748
BET	A	0.09486	0.07471	0.06739
	B	4.45102	4.83224	4.44866
	χ^2 (Reduced Chi-Sqr)	0.0071	0.01544	0.0096
	R^2	0.9714	0.9712	0.9785

Anderson model

The Anderson model was fitted to adsorption data of Bael powder at three temperatures (25 °C, 30 °C, 35 °C) (Fig. 2). Table 2 shows variability in model constants (A, B, C) across the temperatures, with the constant A ranging from 0.16498 to 0.30223, and the constant B ranging from 0.9652 to 1.73695. The reduced chi-square (χ^2) values are relatively low, ranging from 0.03576 to 0.07309, and the coefficient of determination (R^2) values are consistently high, around 0.960, indicating a good fit of the model to the experimental data. The Anderson model provides a satisfactory fit for the adsorption data of Bael powder, with R^2 values above 0.96 across all temperatures, demonstrating that the model

effectively describes the sorption behaviour at different temperatures (Aviara, 2020) [1]. The decreasing trend in the constant A from 25 °C to 30 °C suggests that the interaction between moisture and the material may weaken slightly with increasing temperature, potentially due to higher water vapour pressure at elevated temperatures (Angélica *et al.*, 2010) [3]. Similarly, the fluctuation in constant B indicates variability in the material's moisture absorption capacity with temperature changes. The low χ^2 values reflect minimal discrepancies between the predicted and observed values, confirming that the Anderson model is a decent choice for describing the sorption characteristics of Bael powder in this context.

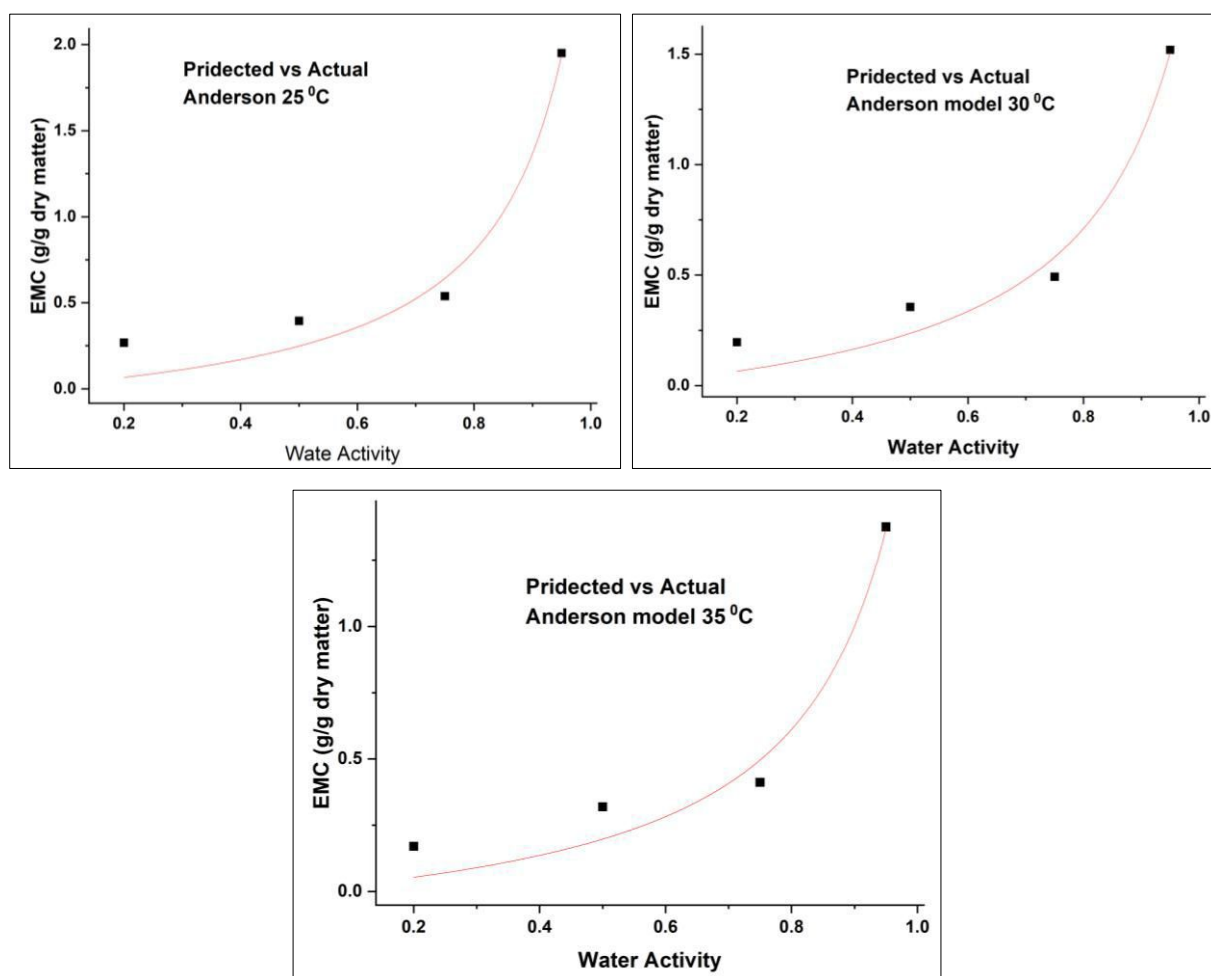


Fig 2: Fitting graphs for Anderson model at 25 °C, 30 °C and 35 °C

GAB model

The GAB model was successfully fitted to adsorption data of Bael powder at temperatures of 25 °C, 30 °C, and 35 °C (Fig. 3). The model parameters A and B were calculated (Table 2), with the value of A decreasing from 13.753 at 25 °C to 8.229 at 35 °C, and B showing relatively consistent values between 0.94426 and 0.96068 across temperatures. The reduced chi-square (χ^2) values ranged from 0.00544 to 0.01269, indicating a good fit, and the R^2 values were consistently high (>0.99), confirming the strong predictive accuracy of the GAB model. The GAB model demonstrated excellent predictive accuracy for the adsorption behaviour

of Bael powder across all three temperatures. The consistency in B values suggests that the strength of water adsorption onto the powder surface did not significantly change with temperature. However, the declining value of A with rising temperatures indicates a reduction in the overall water-binding capacity, potentially due to increased water vapour pressure and higher molecular mobility at elevated temperatures (Rao *et al.*, 2006) [9]. The high R^2 values (>0.99) and low chi-square values confirm that the GAB model is the best representation of the sorption characteristics of Bael powder.

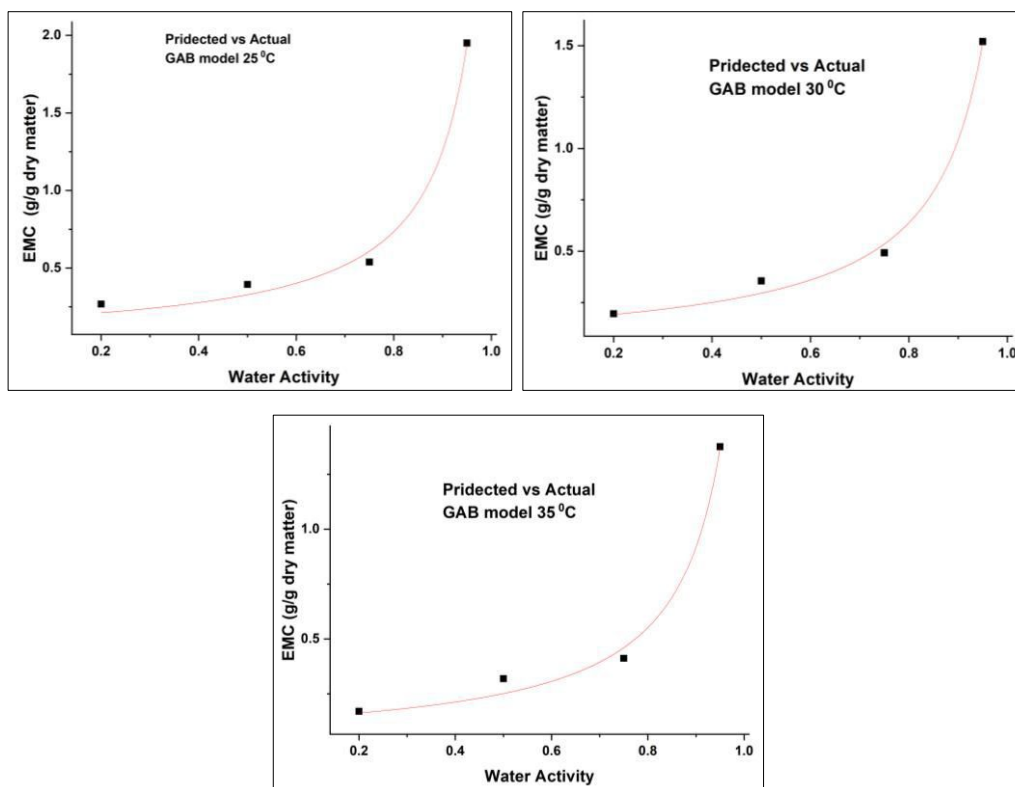


Fig 3: Fitting graphs for GAB model at 25°C, 30°C and 35 °C

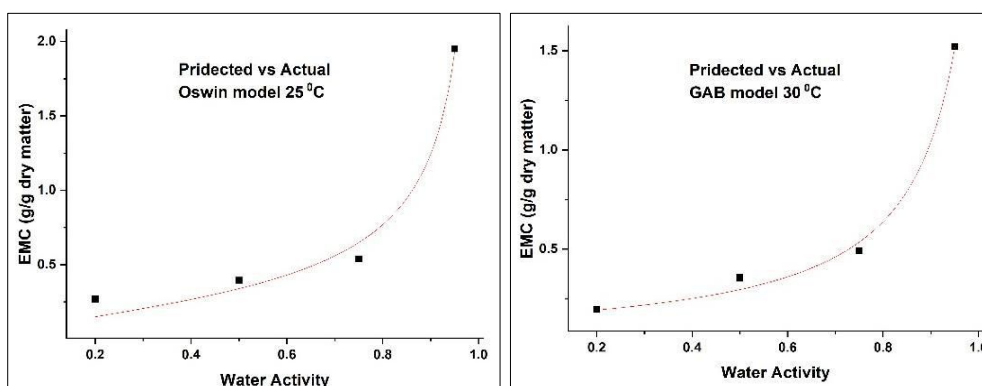
Monolayer Moisture Content (X_m)

The monolayer moisture content (X_m) represents the amount of water that is tightly bound to the surface of the material and is not available for microbial growth or further chemical reactions (Rakshit *et al.*, 2014) ^[16]. In the case of Bael powder, the monolayer moisture content decreased with increasing temperature, from 0.17007 g/g at 25 °C to 0.13183 g/g at 35 °C. This is a typical phenomenon observed in food materials, as elevated temperatures lead to greater molecular activity, reducing the ability of the material to adsorb water.

A reduction in X_m with rising temperature implies that less water is tightly bound to the material at higher temperatures, which can affect the product's shelf-life and stability (Sharma *et al.*, 2023) ^[19] and Shrivastava (1998) ^[20]. The values observed for Bael powder are comparable to those reported in other fruit powders, suggesting that temperature control is critical in maintaining optimal moisture levels and preventing spoilage.

Oswin model

Fig. 4 and Table 2 shows the fitted data to Oswin model to describe the adsorption behaviour of Bael powder at 25 °C, 30 °C, and 35 °C. The model constants A and B were obtained, with A decreasing from 0.33893 at 25 °C to 0.26444 at 35 °C, indicating a reduction in the material's water-holding capacity as the temperature increased. The B constant remained relatively stable, ranging from 0.53554 to 0.59132. The reduced chi-square (χ^2) values were low, between 0.00455 and 0.01482, reflecting a satisfactory fit of the model to the experimental data. The coefficient of determination (R^2) values were consistently high (>0.98), signifying a reliable model fit at all temperatures. The decrease in constant A with rising temperatures suggests a lowered water-holding capacity due to increased molecular movement and reduced hydrogen bonding at higher temperatures, similar findings were reported by Zhang *et al.*, (2022) ^[24] for oil rich tubers.



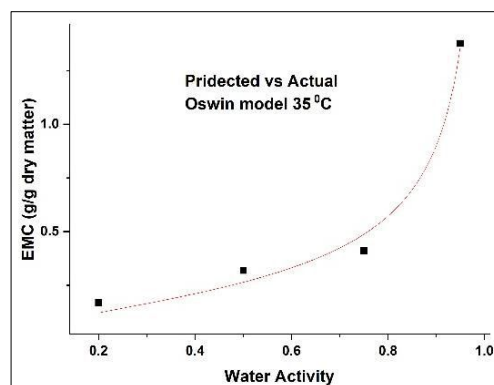


Fig 4: Fitting graphs for Oswin model at 25°C, 30 °C and 35 °C

BET model

The Brunauer-Emmett-Teller (BET) model was employed to fit the adsorption data of Bael powder dried at 65 °C across three temperatures: 25 °C, 30 °C, and 35 °C (Fig. 5). According to data of Table 2, the constant A decreased from 0.09486 at 25 °C to 0.06739 at 35 °C, indicating a reduction in the adsorption capacity with increasing temperature. Constant B showed slight fluctuations, with values of 4.45102 at 25 °C, 4.83224 at 30 °C, and 4.44866 at 35 °C, suggesting relatively stable adsorption characteristics across the temperature range. Reduced chi-square (χ^2) values were low, ranging from 0.0071 to 0.01544, indicating a good fit

between the experimental data and the BET model predictions. Coefficient of determination (R^2) values were high, between 0.9712 and 0.9785, further confirming the model's reliability in describing the adsorption behaviour of Bael powder. The decreasing trend in A with increasing temperature suggests that the adsorption capacity of Bael powder diminishes as temperature rises. This is consistent with the general behaviour of hygroscopic materials, where higher temperatures lead to increased kinetic energy of water molecules, thereby reducing their adsorption onto the powder surface (Shabir *et al.*, 2020)^[18].

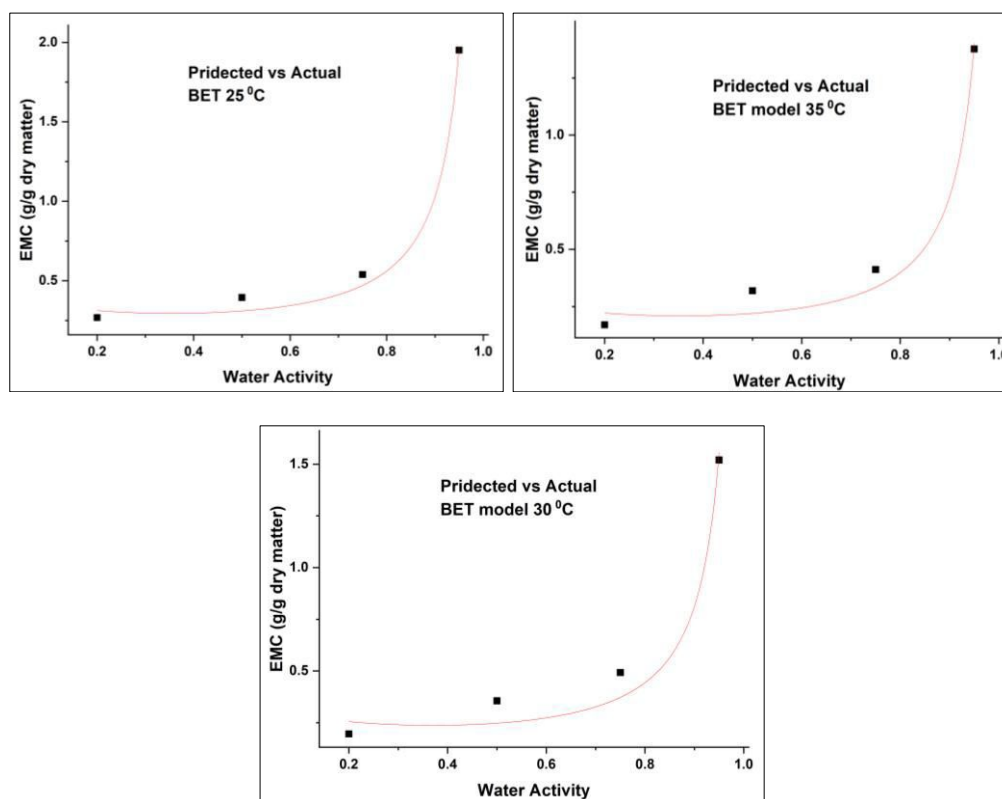


Fig 5: Fitting graphs for BET model at 25 °C, 30 °C and 35 °C

Conclusion

This study offers valuable insights into the hygroscopic behaviour of Bael powder across various relative humidity levels and temperatures, essential for optimizing its storage conditions and extending its shelf-life. Among the four tested models - Anderson, GAB, Oswin, and BET, the GAB model demonstrated the highest accuracy in describing the equilibrium moisture characteristics. Type II sigmoidal

curve in the sorption isotherms, particularly at elevated relative humidity levels, reflects Bael powder's propensity for moisture uptake, which increases as relative humidity rises and decreases with higher temperatures. The monolayer moisture content, which decreased with increasing temperature, indicates that Bael powder's stability can be maintained within specific moisture thresholds. These findings support the selection of suitable

packaging and storage environmental conditions, enhancing Bael powder's commercial viability in functional food and nutraceutical applications.

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