

Moisture Sorption Isotherm of *C. nutans* Herbal Leaves

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Abstract—The moisture sorption isotherms of *Clinacanthus nutans* (*C. nutans*) herbal leaves were established at three different temperatures of 30°C, 40°C, and 50°C, and water activity between 0.3–0.9 using a static gravimetric method. The results showed that equilibrium moisture content of *C. nutans* increased with increasing water activity at a constant temperature for both desorption and adsorption isotherms. In contrast, the equilibrium moisture content decreased when the temperature increased at a constant water activity for all isotherms. The sorption isotherms exhibited Type III behaviour or J-shaped curve according to Brunauer-Emmett-Teller (BET) classification. It was found that Guggenheim-Anderson-de Boer (GAB) and Peleg models were the best-fit to the experimental moisture isotherms. The maximum net isosteric heat of sorption values were found to be 70 kJ/mol and 13 kJ/mol for desorption and adsorption respectively. The moisture sorption isotherms established are essential for optimum design of *C. nutans* dryer and storage conditions.

Keywords—*C. nutans*, herb, sorption isotherm, monolayer moisture content, net isosteric sorption heat

I. INTRODUCTION

Clinacanthus nutans (*C. nutans*) herbal plant is native to tropical and subtropical regions of Asia, predominantly Indonesia, Malaysia, and Thailand. In Malaysia, this herb is known as “Belalai Gajah” and has been listed among the most valuable herbal plants. In fact, the utilisation of its valuable properties is in progress under the government Economic Transformation Programme (ETP). Apart from its diverse ethnopharmacological practices, such as antiviral, anticancer, antidiabetic, and capability to treat various skin problems, it is scientifically proven to exhibit some important bioactivities that are attributable to its

numerous bioactive compounds, mostly phenolic and terpenoids groups. For instance, *C. nutans* was reported to exert an antiviral activity against herpes simplex virus types 1 and 2 (HSV-1 and HSV-2) and Varicella-Zoster Virus (VZV) [1–4]. There were two compounds responsible for HSV inhibitory activity, namely, Digalactosyl Diglyceride (DGDG) and Trigalactosyl Diglyceride (TGDG) [5]. Moreover, various cancer cell lines have been tested against *C. nutans* extracts from solvents of different polarity. It was reported that *C. nutans* possesses an antiproliferative on eight human cancer cell lines, including liver, cervix, lungs, and colon, with different efficacies [6]. Recent finding demonstrated the in vitro cytotoxic effect of *C. nutans* extract fractions on human breast cancer cells [7]. However, fresh *C. nutans* contains high moisture content (> 80%), which may cause its bioactive compound constituents to degrade easily by microorganism spoilage if it is dried insufficiently. For instance, microbial spoilage by *Aspergillus* species produced toxic secondary metabolites, such as aflatoxin and ochratoxin [8].

The appropriate moisture content level for drying and storage can be predicted by establishing moisture sorption isotherms of *C. nutans* leaves. The moisture sorption isotherm is a relationship between product’s Equilibrium Moisture Content (EMC) and the environment’s Relative Humidity (RH) (also noted as water activity (a_w), the RH in decimal) at a constant temperature. The isotherm is further modelled with the established sorption model equations, where the thermodynamic properties of the material can be estimated. There are several frequently used model equations, such BET, GAB and Peleg. Among the aforementioned equations, GAB equation is the most versatile. It consists of three constants, namely, monolayer moisture content (M_0), a constant that related to sorption heat for the first layer (C), and multilayer (k) which is the best-fit model to more than 50% of fruits, meat, and vegetables in the study over 163 types of food materials

[9]. Most importantly, the thermodynamics data are useful in the design calculation of the drying process. For instance, the isosteric sorption heat (q_{st}) is used by engineers to estimate energy needed to dry the product to a certain moisture level. In addition, M_o is important for determining the moisture content of every food material, where this moisture content level provides information on food storage stability. This is due to the strong binding force between water and surface, which reflects insignificant physical and chemical properties changes.

To date, sorption isotherms for various food materials have been developed, such as fig [10], chilli pepper [11], orange, mango, pear fruit peels [12]; rosemary leaves [13]; and persimmon leaves [14]. However, there is no report on the sorption isotherm studies in the literature for *C. nutans* herbal leaves. Therefore, the objectives of this research are to develop moisture sorption isotherms for *C. nutans* leaves under three different temperatures and a_w level between 0.3 and 0.9, to perform mathematical modelling for the sorption isotherms using established model equations, and to estimate the isosteric heat of sorption from the best-fit model equations obtained.

II. MATERIALS AND METHODS

A. *C. nutans* Herbal Leaves as Raw Material

C. nutans herbal leaves were collected from the production plot at Institute of Sustainable Agro Technology, University Malaysia Perlis. The production plot was well-maintained throughout the experimentation time frame to ensure a continuous supply of the raw material for this research. After harvesting, the raw material was immediately washed and separated from the stems and leaves; only leaves of uniform size were selected. Prior to experimentation, the fresh leaves were placed in airtight containers and kept in a refrigerator. Samples of fresh leaves were used for desorption experiment. Meanwhile, for adsorption experiment, the fresh leaves were pre-dried in an oven at 105°C for 24 h ($a_w = 0.19$).

B. Moisture Sorption Isotherms

The moisture sorption isotherms of *C. nutans* leaves were determined at three different temperatures of 30°C, 40°C, and 50°C, and water activity ranging between 0.3 and 0.9 using a standard gravimetric method. Six saturated salt solutions ($MgCl_2$, $Mg(NO_3)_2$, NaCl, KBr, KCl, and KNO_3) were used which correspond to different water activity levels under each temperature (Table I) [15]. All of the solutions were made by dissolving appropriate amount of the salts with distilled water. A total of 12 hermetic jars with salt solutions were equilibrated under each temperature for at least 24 h before the experiment was carried out. The fresh and pre-dried samples were then weighed and distributed in glass petri dishes. The samples were later placed on a wire mesh stand inside the jars and separated between desorption and adsorption experiments. About 1 g of thymol was put in a small container without lid and placed in the glass jars with a_w more than 60% to prevent microbial growth on the samples.

Throughout the experiment, the samples were re-weighed every two days until the change of weight was

less than 0.001 g within three consecutive readings. At that stage, the samples reached an EMC. It took 4–8 weeks for the samples to equilibrate, depending on the experiment conditions. The EMCs were calculated using Eq. (1):

$$EMC = \frac{w_t - w_{dm}}{w_{dm}} \quad (1)$$

where, w_t is sample weight, and w_{dm} is the sample dry matter weight. The dry matter weight was determined using oven method (105°C, 24 h). The equilibrium moisture content was plotted against water activity to demonstrate the relationship under each temperature. All of the EMC data gained in the experiments were performed in three replications.

TABLE I. RELATIVE HUMIDITY LEVEL UNDER TEMPERATURE OF 30°C, 40°C, AND 50°C

No.	Salt	RH (%)		
		30°C	40°C	50°C
1.	Magnesium chloride ($MgCl_2$)	32.44	31.6	30.54
2.	Magnesium nitrate ($Mg(NO_3)_2$)	51.4	48.42	45.4
3.	Sodium chloride (NaCl)	75.1	74.68	74.4
4.	Potassium bromide (KBr)	80.27	79.43	79.02
5.	Potassium chloride (KCl)	83.6	82.32	81.2
6.	Potassium nitrate (KNO_3)	92.3	89.03	84.78

C. Mathematical Modelling

The moisture sorption isotherms of *C. nutans* leaves were fitted into ten established mathematical model equations, such as Oswin, Peleg, BET, and GAB (Table II). The non-linear regression analysis was used to obtain each constant in the model equations. The constants were applied to generate and compare the predicted EMC with the experimental EMC values. Good criteria of the best-fit model were based on statistical parameters, namely, highest correlation coefficient (R^2) value (Eq. (2)), lowest mean relative percentage deviation modulus (P) (Eq. (3)), Root-Mean-Square Error (RMSE) (Eq. (4)), and reduced chi-squared (χ^2) (Eq. (5)) values. The curve fitting procedure was conducted using the Microsoft Excel Solver.

$$r^2 = 1 - \frac{\sum_{i=1}^n (EMC_{i\ exp} - EMC_{i\ pre})^2}{\sum_{i=1}^n (\overline{EMC}_{exp} - EMC_{i\ pre})^2} \quad (2)$$

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

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

$$\chi^2 = \frac{\sum_{i=1}^N (EMC_{exp,i} - EMC_{pre,i})^2}{N-n} \quad (5)$$

where, EMC_{exp} is the experimental equilibrium moisture content, EMC_{pre} is the predicted equilibrium moisture content, N is number of observations and n is number of constants.

TABLE II. LIST OF MODEL EQUATIONS FOR MATHEMATICAL MODELING ANALYSIS

No.	Model	Equation	Reference
1.	GAB	$EMC = \frac{M_o C K a_w}{[(1 - K a_w)(1 - K a_w + C K a_w)]}$	[16]
2.	BET	$EMC = \frac{M_o C a_w}{(1 - a_w) + (C - 1)(1 - a_w) a_w}$	[17]
3.	Oswin	$EMC = A \cdot \left(\frac{a_w}{1 - a_w}\right)^B$	[18]
4.	Modified Oswin	$EMC = A \cdot \left(\frac{a_w}{1 - a_w}\right)^B$	[18]
5.	LESPAM	$EMC = A \times \exp\left(\frac{B a_w}{T}\right) + C$	[19]
6.	Enderby	$EMC = A \cdot \left(\frac{a_w}{1 - a_w}\right)^B$	[20]
7.	Caurie	$EMC = \exp(A + B \cdot a_w)$	[21]
8.	Peleg	$EMC = A(a_w)^C + B(a_w)^D$	[22]
9.	Smith	$EMC = A + B \log(1 - a_w)$	[23]
10.	Iglesias & Chirife	$EMC = A + B \cdot \left(\frac{a_w}{1 - a_w}\right)$	[24]

D. Net Isosteric Heat of Sorption

Energy needed to dry *C. nutans* leaves until a desired moisture content level can be estimated from the net isosteric heat of sorption ($q_{st,n}$). It indicates the intermolecular attractive forces between the active sites and water vapour [16]. The Clausius-Clapeyron equation (Eq. (6)) was used to calculate the $q_{st,n}$.

$$\ln a_w = -\left(\frac{q_{st,n}}{R}\right)\left(\frac{1}{T}\right) + C \quad (6)$$

where, R is the universal gas constant (8.314 kJ/mol. K), T is temperature (K), and C is a constant. The best-fit model equation was used to estimate the EMC at the corresponding a_w . Then, a graph of $\ln a_w$ versus $(1/T)$ was plotted within the estimated EMC. The $q_{st,n}$ values were measured from the slope of the curve by linear regression analysis and they are assumed constant over the studied temperature range. In fact, the $q_{st,n}$ can be determined at every value of equilibrium moisture content. Graph of $q_{st,n}$ was plotted against EMC. The $q_{st,n}$ is also defined as difference between isosteric heat of sorption and heat of vaporization of pure water (Eq. (7)).

$$q_{st,n} = q_{st} - \Delta H_{vap} \quad (7)$$

where q_{st} is the isosteric heat of sorption (J/mol), ΔH_{vap} is the heat of vaporization of pure water (40.7 kJ/mol).

E. Statistical Analysis

Analysis of Variance (ANOVA) was performed at 95% confidence level ($p < 0.05$) using R Software. Full factorial randomized complete block design experiment was selected. From the ANOVA result, factors that showed significant interaction were further analysed for mean comparison using Least Square Difference (LSD) approach.

III. RESULTS AND DISCUSSION

A. Effects of Temperature and Water Activity on Equilibrium Moisture Content of *C. nutans* Leaves

Figs. 1 and 2 show the moisture sorption isotherms of *C. nutans* leaves, illustrating the relationship between EMC and a_w at a constant temperature. As it can be seen from the figures, the EMC decreases with the increasing temperature from 30°C to 50°C at a constant a_w . The decrement of EMC is due to reduction of attractive forces between the water molecules which result from increase of water excitation state at the higher temperature. In contrast, EMC increased as the a_w increased from 0.3 to 0.9 for both desorption and adsorption isotherms at a constant temperature. For desorption at higher a_w , the vapour pressure difference between fresh leaf sample and the surrounding environment is small, thus weakening the intermolecular forces between water and active sites which resulted in high EMC. On the other hand, during adsorption process at higher a_w , the vapour pressure difference between dried sample and the surrounding is high. Therefore, the strong attractive forces between them had promoted better adsorption efficiency, which resulted in higher moisture content.

The sorption isotherms of *C. nutans* leaves were classified under Type III (J-shaped) according to BET classification. This Type III sorption behaviour explains the water holding ability of food [25]. It is characterised by the ability of the food material to hold a small amount of water at a lower a_w level, and larger amount of water at higher a_w level. This trend can be observed in the *C. nutans* leaves isotherms, where initially, the EMC increased gradually but began to increase sharply when $a_w > 0.7$. The stiffness of the curve is due to the dissolution of sugars or other soluble crystalline components with the adsorbed water. Similar trend was reported for other food materials, such as fruit peels dietary fibre [12], black peppercorns [8], and freeze-dried mango [26].

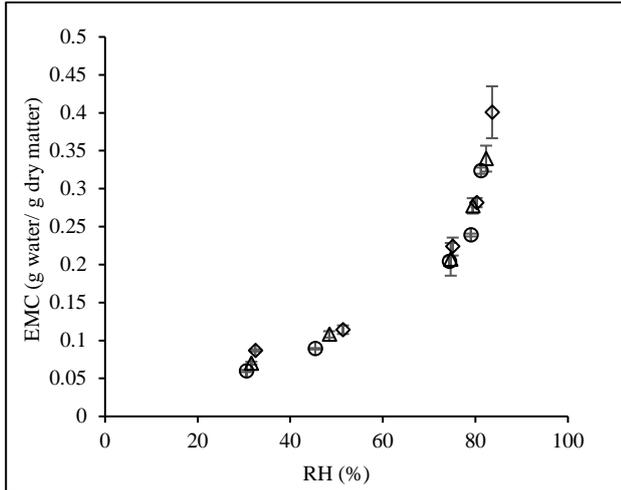


Figure 1. Desorption isotherms of *C. nutans* leaves at different temperatures 30°C (◇), 40°C (Δ) and 50°C (○).

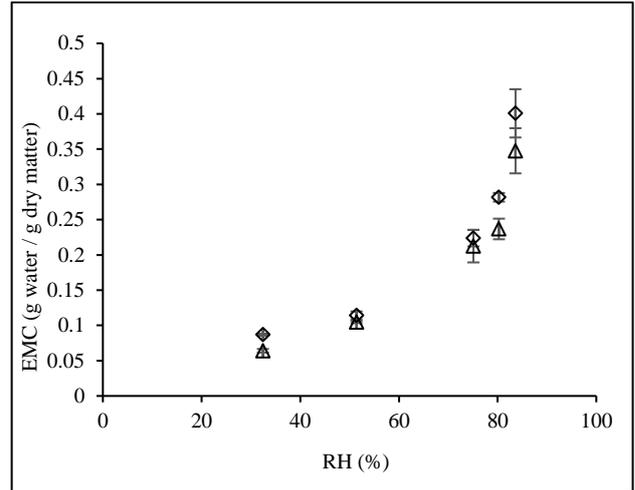


Figure 3. Desorption (◇) and adsorption (Δ) isotherms of *C. nutans* leaves showing hysteresis at 30°C.

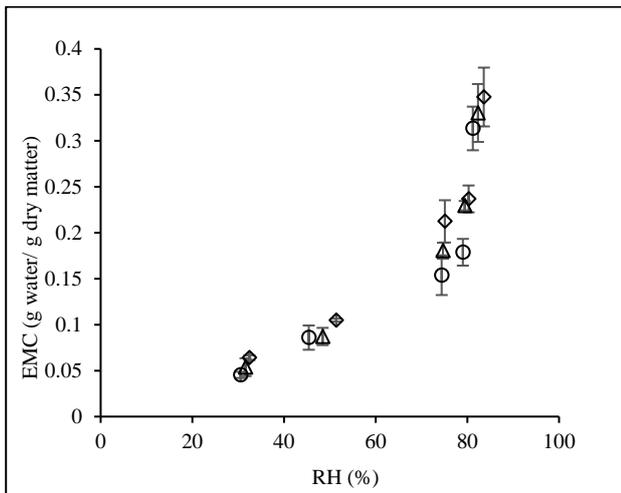


Figure 2. Adsorption isotherms of *C. nutans* leaves at different temperatures 30°C (◇), 40°C (Δ) and 50°C (○).

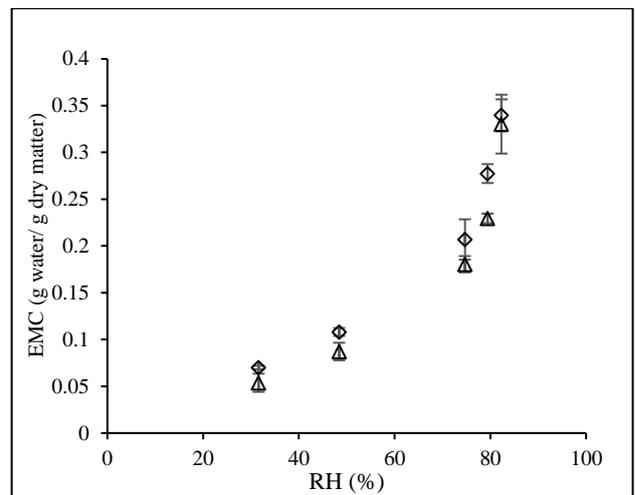


Figure 4. Desorption (◇) and adsorption (Δ) isotherms of *C. nutans* leaves showing hysteresis at 40°C.

B. Moisture Sorption Isotherm Hysteresis

Results from Figs. 3–5 show the desorption and adsorption isotherms of *C. nutans* leaves at 30°C, 40°C, and 50°C. The figures demonstrate that each isotherm exerted sorption hysteresis for the entire RH levels. Sorption hysteresis is a difference of EMC between desorption and adsorption. The difference represents energy that is required for filling and emptying the pores and sorption sites of the material [27]. It is also related to the nature and state of component in a food [28]. For *C. nutans* leaves, the EMC for adsorption was observed to be lower than desorption because of the pre-dried samples. Drying modifies and deactivates the binding sites due to shrinkage. This reduced the ability of the samples to pick up moisture [29]. In contrast, during desorption, the narrow ends of surface pores are trapped and hold water internally below the water activity where the water should be released, thus resulting in higher moisture content of the leaf. Most of the sorption isotherm reported in literatures exerted hysteresis, such as rosemary leaves [28] and black peppercorns [8].

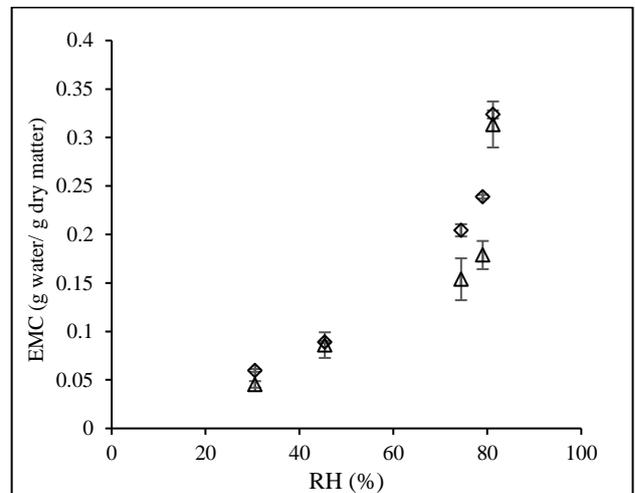


Figure 5. Desorption (◇) and adsorption (Δ) isotherms of *C. nutans* leaves showing hysteresis at 50°C.

C. Mathematical Modelling of *C. nutans* Sorption Isotherm

Mathematical modelling was performed to fit the experimental moisture sorption isotherms of *C. nutans* leaves with predicted isotherms estimated by the established mathematical model equations. It is a useful tool in order to estimate important parameters involved in the design of drying process and storage requirement from the best fitting model.

Table III shows the result of the values of the constants retrieved from each model by the non-linear regression analysis as well as the statistical evaluation of each model. The GAB model equation was found to be the most suitable to describe the desorption characteristic at 40°C and 50°C, respectively, based on the highest R^2 (> 0.99) and lowest P (3.33%–4.87%), RMSE (0.007–0.012), and χ^2 (0.0001–0.0003) values. However, the statistical evaluation results for the desorption isotherm of 40°C showed similar values with the Enderby model, as shown in Table III. Thus, Enderby model also could be used in describing the desorption behaviour.

Peleg model gave a good-fitting to the rest of the isotherms. It presented the excellent R^2 values > 0.99 except for adsorption isotherm at 50°C which showed a slightly low R^2 of 0.94. The P value of less than 10% is considered acceptable [9]. Peleg model had been reported to be the best-fitting to a number of food materials over the other frequently used models [8, 12, 30–32].

Monolayer moisture content (M_0) of *C. nutans* leaves was calculated from the GAB and BET regression analyses. The M_0 needs to be elucidated, since it provides a critical moisture content where the shelf-life of a material could be extended. At the M_0 , food spoilage and physical changes are slowed down due to strong binding of water to the active sites [33]. The M_0 for *C. nutans* from GAB was 0.03–0.07 g water/ g dry matter) and 0.05–0.07 g water/g dry matter using the BET (Table III). However, the BET equation is limited for a range of a_w between 0.05 and 0.45, therefore, the M_0 determined by GAB may be considered [27]. The M_0 of *C. nutans* was comparable with honeydew seed, orange peel, black peppercorn, and persimmon leaves [8, 12, 14, 31].

TABLE III. CONSTANT VALUES OF MODEL EQUATIONS AND STATISTICAL EVALUATION RESULT

Model Equation	Parameter	Desorption Temperature (°C)			Adsorption Temperature (°C)		
		30	40	50	30	40	50
GAB	M_0	0.070581	0.051611	0.040681	0.058009	0.05345	0.03342
	K	0.969625	1.026175	1.069542	0.986585	1.00535	1.074239
	C	6.111559	42.73145	66402.07	6.18862	4.058599	66401.8
	R^2	0.987055	0.998349	0.991223	0.99203	0.984607	0.935215
	P (%)	7.810372	3.336819	4.871726	4.209722	6.697988	14.08524
	RMSE	0.021884	0.007049	0.012265	0.016896	0.018388	0.029309
		0.000958	9.94E-05	0.000301	0.000571	0.000676	0.001718
BET	M_0	0.053666	0.065958	0.068077	0.050214	0.056122	0.06186
	C	9945365	2.817116	1.731422	9945365	3.144755	1.094127
	R^2	0.974605	0.990053	0.964462	0.988737	0.984383	0.906272
	P (%)	7.293892	9.952932	13.56361	7.381528	7.907562	23.92569
	RMSE	0.003027	0.017305	0.024585	0.020321	0.01852	0.035697
		0.001853	0.000449	0.000907	0.000619	0.000515	0.001911
Oswin	A	0.113016	0.082089	0.107399	0.108914	0.077189	0.055952
	B	0.709671	0.936226	0.712466	0.72309	0.883323	1.078884
	R^2	0.98523	0.988887	0.965934	0.986628	0.982871	0.913811
	P (%)	9.303212	14.93039	9.46616	10.7443	12.48032	26.26506
	RMSE	0.008043	0.020763	0.024093	0.033574	0.019796	0.03546
		0.000824	0.000647	0.000871	0.001691	0.000588	0.001886
Modified Oswin	A	0.017302	0.015821	0.016356	0.019813	0.015558	0.014771
	B	0.00319	0.001657	0.001949	0.002345	0.001541	0.000824
	C	0.709671	0.936229	0.783233	0.786342	0.883322	1.078883
	R^2	0.98523	0.988887	0.965935	0.990677	0.982871	0.913811
	P (%)	9.303226	14.93044	9.466184	8.990927	12.48027	26.26503
	RMSE	0.008043	0.020763	0.024093	0.018542	0.019796	0.03546
		0.001648	0.001293	0.001741	0.001031	0.001176	0.003772

Enderby	A	0.098463	1.750973	0.040867	41.66769	1.190611	0.033009
	B	0.014391	-33.1235	1.067364	-1139.61	0.001541	1.080755
	C	0.061601	0.052707	0.055757	0.060918	0.883322	0.943964
	D	0.974563	1.026521	0.351197	0.982266	0.998919	-21.7251
	R ²	0.984992	0.998348	0.986436	0.992178	0.985171	0.935475
	P (%)	9.910111	3.328907	13.2672	4.771563	6.70297	14.48896
	RMSE	0.010425	0.007052	0.018147	0.016739	0.018047	0.029213
			0.001707	0.000149	0.000988	0.000841	0.000977
LESPAM	A	0.01112	0.01112	0.029084	0.004468	0.008223	0.000604
	B	7.958569	7.958569	7.403396	8.921477	8.600182	11.99156
	C	0.084391	0.084391	0.054226	0.07554	0.05986	0.062229
	R ²	0.993237	0.986353	0.983169	0.991626	0.988935	0.940707
	P (%)	4.76712	9.59952	7.243061	10.09888	9.07979	17.32383
	RMSE	0.000997	0.030255	0.029946	0.017319	0.01559	0.028004
	χ^2	0.00075	0.002746	0.00269	0.0009	0.000729	0.002353
Peleg	A	0.118412	0.094821	0.082755	0.195718	0.121409	0.128268
	B	0.997606	0.994405	0.992482	1.00477	1.003335	1.058764
	C	0.250654	0.265109	0.275734	0.9741	0.637516	0.723451
	D	7.409927	7.437377	7.454521	10.37284	8.515133	12.35264
	R ²	0.993913	0.985875	0.970959	0.993883	0.990338	0.945341
	P (%)	4.420674	4.867251	7.739819	4.379845	6.574481	12.96243
	RMSE	0.001096	0.027833	0.023964	0.014802	0.014568	0.026888
	χ^2	0.000675	0.002324	0.001723	0.000657	0.000637	0.002169
Caurie	A	-5.63459	-6.58883	-5.7301	-6.46112	-6.22438	-6.92393
	B	5.618393	6.772341	5.672442	6.48314	6.162757	6.938612
	R ²	0.971205	0.968597	0.941121	0.972156	0.970058	0.901263
	P (%)	24.49761	28.71668	26.47757	27.79891	2.069595	35.82684
	RMSE	0.026432	0.041089	0.036353	0.038787	0.030997	0.042106
	χ^2	0.002317	0.002532	0.001982	0.002257	0.001441	0.005319
Smith	A	-0.07476	-0.07788	-0.0451	-0.09194	-0.06986	-0.04031
	B	0.260086	0.260005	0.217891	0.25351	0.225527	0.185964
	R ²	0.928793	0.879879	0.889323	0.910758	0.907169	0.822365
	P (%)	22.02424	27.3786	18.3061	29.50512	25.46575	27.13932
	RMSE	0.024336	0.060129	0.043108	0.056536	0.045155	0.048471
	χ^2	0.003948	0.005423	0.002787	0.004794	0.003058	0.007048
Iglesias and Chirife	A	0.079506	0.028618	0.018808	0.054846	0.026438	0.013067
	B	0.049982	0.067926	0.069493	0.049553	0.057798	0.059705
	R ²	0.974605	0.992982	0.968149	0.988737	0.985205	0.907191
	P (%)	9.769307	8.070279	10.90455	8.411239	6.328164	18.96554
	RMSE	0.0068	0.014534	0.023125	0.020085	0.018027	0.035036
	χ^2	0.001408	0.000317	0.000802	0.000605	0.000487	0.003682

D. Net Isotheric Heat of Sorption

Net isotheric heat of sorption, $q_{st,n}$, is the difference between isotheric heat of sorption, q_{st} , and the heat of vapourisation of water, ΔH_{vap} . The $q_{st,n}$ is useful for the

estimation of actual energy required for drying of a material to a certain moisture content.

Fig. 6 shows the result for the $q_{st,n}$ value for *C. nutans*. From the abovementioned figure, at a lower range of equilibrium moisture content between 0.05–0.1 g water/g

dry matter, the $q_{st,n}$ for desorption decreased from maximum value of 70 kJ/mol to 8 kJ/mol, while for adsorption, the $q_{st,n}$ increased slightly from 4 kJ/mol to 13 kJ/mol. Thereafter, the $q_{st,n}$ reduced slightly until it equals to ΔH_{vap} . The higher $q_{st,n}$ value represents the difficulty of water movement from interior to the surface of the samples [34]. As the equilibrium moisture content increased, the $q_{st,n}$ dropped until only a little change was observed. It is due to the availability of polar active sites for sorption process that has decreased and occupied with the water molecules [8]. At this stage, water molecules act as it is in liquid form, therefore, the higher the moisture content of the materials, lesser energy is needed in the drying process [13].

In addition, it was also clearly observed that the $q_{st,n}$ for adsorption was lower than that of the desorption. It means that more energy is needed to desorb water from wet leaves than to adsorb water from dried leaves. As shown in Fig. 6, at lower moisture content, the $q_{st,n}$ for desorption was much greater than that for adsorption. However, the difference became insignificant at higher moisture content. This trend was also observed in other types of food material [8, 13, 31].

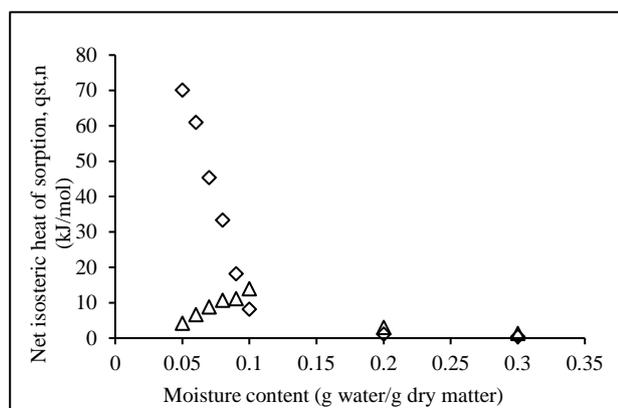


Figure 6. The net isosteric heat of sorption for desorption (◇) and adsorption (△).

IV. CONCLUSION

The moisture sorption isotherms of *C. nutans* herbal leaves were successfully developed at water activity ranging between 0.3 and 0.9 and temperatures of 30°C, 40°C, and 50°C. Outcome of the effects of temperature and water activity on the leaves' equilibrium moisture content were as expected, and it was comparable with other types of food materials. The non-linear regression analysis of the experimental isotherms was shown to be best-fit to the GAB and Peleg models. Both models are frequently reported as the best-fit to other experimental isotherms. The M_0 values of the leaves were retrieved from the mathematical modelling of GAB and BET equations. It is a critical moisture content that determines the stability of the leaves after drying. Furthermore, the GAB and Peleg equations were used to predict the net isosteric heat of sorption ($q_{st,n}$) value at every moisture content level of the *C. nutans* leaves. The $q_{st,n}$ values obtained were as expected and similar to other food materials, where the values decreased as moisture content increased. It

represents the amount of energy needed for removing a known amount of water during the drying of *C. nutans* leaves. In addition, it could be a useful parameter for drying and storage design consideration. In a conclusion, the moisture sorption isotherms established for *C. nutans* leaves would be such important information for herbal processing standardisation that aims to produce premium quality dried herbal raw materials.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHORS CONTRIBUTION

S. Abdullah conducted experiments, analysed data, wrote the research paper; Y. A. Yusof, N. N. Abdul Karim Shah, F. S. Mohd Salleh, and M. A. Ali performed a technical review; N. Abdul Razak managed the project financial; all authors had approved the final version.

FUNDING

This research project was supported by Ministry of Higher Education Malaysia under Fundamental Research Grant Scheme (Grant no: FRGS/1/2018/TK02/UNIMAP/03/3).

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