International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 12 No. 1s, 2026
https://www.theaspd.com/ijes.php

The Isothermal Sorption – Experimental and mathematical investigations of Orange Peel (Citrus sinensis)

Asmaa Chentoufi[1], Amel Saad[2], Nawel Chiekh[3], Abdelhadi Seghir[4], Boumediene Touati[5]

[1]Asmaa Chentoufi, Laboratory of Chemistry and Environmental Science (LCSE), University Tahri Mohammed of Becher, Algeria, and Laboratory of Energetic in Arid Zones (ENERGARID), Team of Solar Resources and its Applications (GSA), University Tahri Mohammed of Bechar, Algeria, Email : asmaa.chentoufi@univ-bechar.dz ORCID : 0009-0006-6908-5622
[2]Amel Saad, Laboratory of Energetic in Arid Zones (ENERGARID), Team of Solar Resources and its Applications (GSA), University Tahri Mohammed of Bechar, Algeria, Email : saad.amel@univ-bechar.dz ORCID : 0000-0002-3233-6516
[3]Nawel Chiekh, Laboratory of catalysis and synthesis in organic chemistry, University Abou Bekr Belkaid, Tlemcen, Algeria.E-mail : cheikh.naoual@univ-bechar.dz, ORCID : 0000-0003-2667-7362
[4]Abdelhadi Seghir, Laboratory of Energetic in Arid Zones (ENERGARID), Team of Solar Resources and its Applications (GSA), University Tahri Mohammed of Bechar, Algeria, E-mail : seghir.abdelhadi@univ-bechar.dz ORCID : 0000-0002-0998-2210
[5]Boumediene Touati, Laboratory of Energetic in Arid Zones (ENERGARID), Team of Solar Resources and its Applications (GSA), University Tahri Mohammed of Bechar, Algeria, Email : touati.boumedienne@univ-bechar.dz, ORCID : 0000-0002-6990-9787
Corresponding Author: Asmaa.Chentoufi, E-mail: asmaa.chentoufi@univ-bechar.dz

Received: 12-11-2025 **Accepted:** 11-05-2026 **Published:**18-05-2026

***SUMMARY*:**
During a forced convection drying and storage operation, the equilibrium water content of a product to be dried is critical. These figures are frequently derived using isothermal sorption curves. The calculation of isotherms is a necessary step in determining the distribution and intensity of water connections in products. Moisture equilibrium data for adsorption and desorption of water from orange peel (Citrus sinensis) were investigated at tree temperatures 30-40-50 C° and water activity ranging from 0.05 to 0.9 to study the influence of the temperature on the equilibrium curves of the orange peel. Nine models, namely the GAB, BET, Adam and Shove & Henderson Thompson, Caurrie, Oswin Smith Hailwood Horrobon Langmuir equations were fitted to the sorption data. The hysteresis effect was observed. The net isosteric heats for orange peel were determined by the application of the Clausius-Clapeyron equation to sorption isotherm obtaining from the best fitting equation.
KEYWORDS: *Sorption isotherm, static gravimetric method, models, orange peel (Citrus Sinensis), equilibrium water content, isosteric heat of sorption*

INTRODUCTION:

Citrus fruits represent one of the most important fruit crops in the world.
Oranges are the most consumed because of their good flavor, high nutritional value and rich composition of bioactive molecules (more than 170 phytochemical compounds are described [1,2]
The food processing industry and consumption
Citrus fruits produce enormous amounts of peels, pulps, and seeds as byproducts. These latter are frequently put back into the wild and have a margin of 45 to 60% of the entire fruit [3,4]. During the processing of citrus fruits, shells are the main by-products, and when left untreated, they will cause environmental pollution [5, 6]. The shells are utilized for melas to feed animals, for fibers (pectin), and as fuel [7]. Based on the most recent studies, these shells are a resource for biologically active compounds. They are known to have a high content of vitamin C and secondary metabolites such as phenolic compounds especially flavonoids and essential oils [8, 9]. The last compounds being the most important because of their various biological activities such as antimicrobial, anti-fungal, anti-inflammatory, and antioxidant activities [10].
The determination of sorption isotherms is of important interest in any drying process. These isotherms allow to know the final water content of a product exposed to defined drying conditions (temperature and humidity), and provides information on limiting conditions during modelling, especially when the material is hygroscopic. Food storage and shelf life. Their knowledge informs us about the hygroscopic or hydrological balance of the product in question.

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 12 No. 1s, 2026
https://www.theaspd.com/ijes.php

Only from such curves, the stability of the product after drying can be established, and in this way, the content of water in the product is known.
This equilibrium is characterized from these curves whose experimental determination requires a large number of measurements.
They are also useful during a convective drying process. Indeed, it is from the sorption curves that we determine the content of final water of a product to be dried. Also, it gives us information about heat isosteric and the lifespan of the product.
The sorption isotherm is a curve that depends on the temperature, which is the ratio of the moisture content of the product studied at different relative humidity environments ambient.

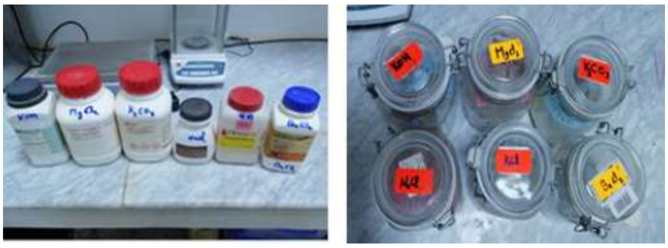

Figure 1. Samples placed in jar for the sorption isotherms test

2.1.2 Determination of sorption isotherms

We have realized this work at level of team of Solar Resource and its Application (GSA), of our Laboratory of Energetic in Arid Zones, (ENERGARID) University TAHRI Mohamed of Bechar
Orange (Citrus sinensis) were purchased from local market of Bechar, Algeria in January and February 2021.
Drying oven.
Six Jar containing saline solution.
Sample carrier.
Saturated saline solution: KOH, MgCl2, K2CO3, NaCl, KCl, and BaCl2.
A fraiche mass of 0.07g for desorption and 0.05g for adsorption
The Hygroscopic equilibrium was attained after 10 days for desorption and adsorption.
The saturated saline solution used are KOH, MgCl2, K2CO3, NaCl, KCl, and BaCl2.
The equilibrium moisture content (EMC) is given by [11]:

$$X_{eq}=(M_w-M_d)/M_d \quad (1)$$

The temperature of the thermostatic bath was changed, and the same experiment was repeated for desorption and adsorption processes at 30, 40, and 50 °C.

Table 1. Selected salts used for preparing salt solution and their corresponding water activities:

Salt		Water activity		
		30°C	40°C	50°C
KOH		0.0738	0.0626	0.0572
$MgCl_2$		0.3238	0.3159	0.3054
K_2CO_3		0.4317	0.423	0.4091
NaCl		0.7511	0.747	0.744
KCl		0.8362	0.8232	0.812
$BaCl_2$		0.898	0.891	0.8823

NB: befor beginning the prepation of the six salt solutions, we consulted the different values of the solubility of the salt used.

Table 2. Used salts solubility

solution	KOH	$MgCL_2$	K_2CO_3	NaCL	KCL	$BaCL_2$
Solubility(g/l)	1100	542	1120	359	340	360

2.1.3 Modeling of sorption isotherm

The relationship description between Xeq, Aw and temperature T was confirmed using the following nine models, which were identified and selected to fit sorption isotherm for the experimental data of orange peel. The identified equations are as shown in table 3 below

Table 3. Mathematical models used to describe desorption and adsorption isotherms of orange peel

Name of the model	Model expression	Reference
Henderson Thompson	$\left(\frac{ln(1-a_w)}{-a(T+b)}\right)^{1/c}$	(14)
Adam and Shove	$X_{eq} = A + BA_w + CA_w^2 + DA_w^3$	(15)
Modified Oswin	$X_{eq} = (A + BT)(A_w/(1 - A_w))^C$	(16)
Caurrie	$X_{eq} = exp(A + B \times A_w)$	(17)
GAB	$X_{eq} = A.B.C.a_w/[1 - a_w][1 - B.a_w + B.C.a_w]$	(18)
Smith	$X_{eq} = A - B\,ln(1 - a_w)$	(19)
Langmuir	$X_{eq} = A.B.a_w/(1 + b.a_w)$	(20)
BET modified	$X_{eq} = (A + BT).C.a_w/[1 - a_w][1 - a_w + C.a_w]$	(21)
Hailwood Horrobn	$Xeq = \left(\frac{1800}{C}\right)\left(a.b.\frac{aw}{100} + a.b.c\right) + (\frac{1800}{C})(b.aw/100 - b.aw)$	(17)

2.2Data analysis:

The goodness of fit was determined by using three statistical parameters:

- the coefficient of correlation (r) given by the software Curve Expert Professional 2.7.3
- the relative mean error (RME) given by the equation

$$RME = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{X_{eqi,\exp} - X_{eqi,pre}}{X_{eqi,\exp}}\right| \quad (2)$$

the standard error of the moisture content of the plant (SEM) expressed by equation (7):

$$SEM = \sqrt{\frac{\sum_{i=1}^{N}\left(X_{eqi,\exp} - X_{eqi,pre}\right)^2}{d_f}} \quad (3)$$

2.1.2 Determination of the net isosteric heat of sorption

The following is the equation that can be used, directly provided by the Clausius-Clapeyron equation, for determination of net isosteric heat of sorption from desorption data of moisture

$$\ln(A_w) = -\left(\frac{Q_{st}}{R}\right)\left(\frac{1}{T_k}\right) + K \quad (4)$$

In this case, Tk is the absolute temperature (K), R is the universal gas constant (kJ/mol K), aw is the water activity (dimensionless), and K is a constant. Plotting the sorption isotherms as l n (aw) vs 1/T for fixed equilibrium moisture content values results in the isosteres curves. At every equilibrium moisture content value, the net isosteric heats of sorption can be computed using the slope of the isosters curves, which equals – (qst/R).

The sorption isotherms are plotted as ln (Aw) versus 1/T for fixed values of equilibrium moisture contents the isosteres curves

3. RESULTS AND DISCUSSION

3.1 Sorption isotherm of orange peel (Citrus sinensis)

The experimental results of the desorption isotherm of orange peel Citrus sinensis (obtained at 30, 40 and 50◦C) is given in Fig [2.3]

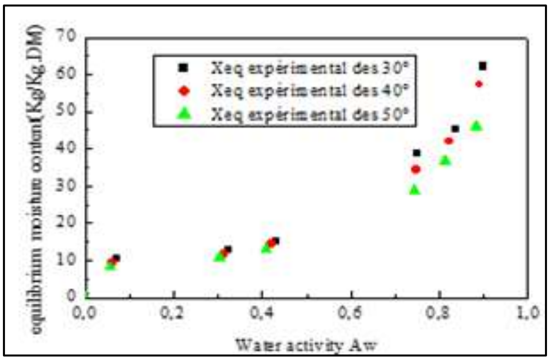

Figure 2. Desorption isotherm of orange peel experimental points at three temperatures

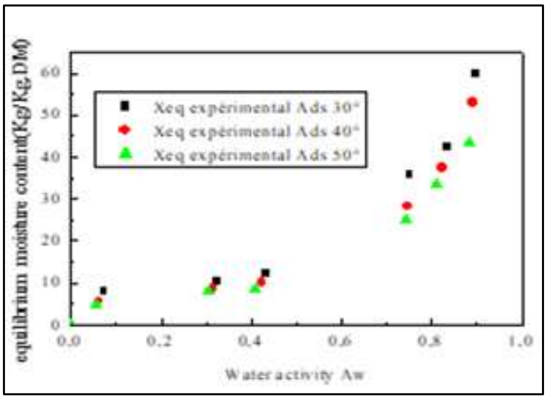

Figure 3. Adsorption isotherm of orange peel experimental points at three temperatures

The curves of the sorption isotherms are sigmoidal in shape. These results are near to other results that are available in the literature.

For greater temperatures, the excitation state of the molecules is higher, which provides reasons for reduction in the forces of attraction of the water molecule to each other. For constant temperatures, the water activity raises with the Xeq balance water content. At every temperature, Al isotherms demonstrate a rise in the equilibrium moisture content as water activity increases. This can be explained by the molecules' excited states brought on by an increase in temperature. [23], [24].

3.2 Modeling sorption isotherms.

The findings of the nonlinear regression analysis of the orange peel's desorption and adsorption isotherms obtained at 30, 40, and 50∘C are displayed in Tables 4 and 5, respectively. For the temperatures under study, the standard error (S), correlation coefficient (r), and percent average relative deviation (P) of the nine models—GAB, BET, Handerson-Thompson, Adam and Shove, Caurrie, Oswin, Smith, Haillwood Horroben, and Langmuir—fitted to the desorption and adsorption data are provided**.**

There are temperatures listed

Figures 4 and 5 present the experimental values of the equilibrium moisture content of orange peel sorption for three working temperatures (30, 40, and 50°C) and for water activity ranging from 5-90%, as well as the curves calculated by the GAB equation. For a given water activity, the equilibrium moisture content decreases as the temperature increases.

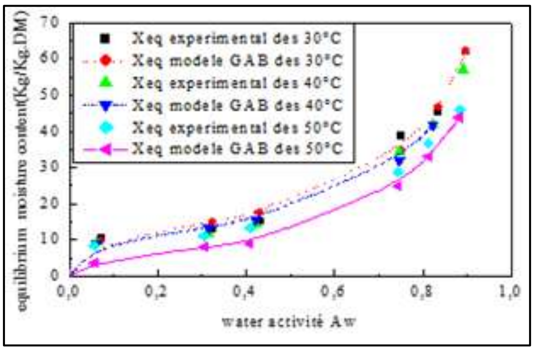

Figure 4. Desorption isotherm of orange peel fitted by GAB model

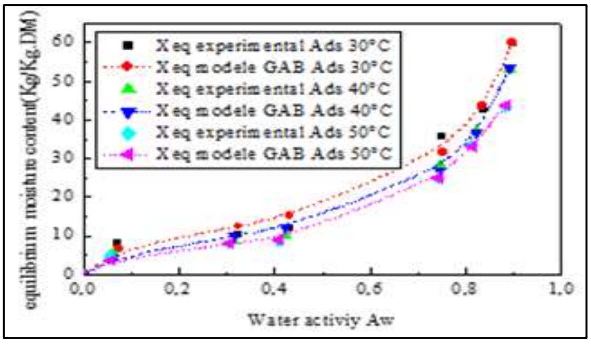

Figure 5. Adsorption isotherm of orange peel fitted by GAB model

Table1: Results of fitting of the desorption isotherms of orange peel (Citrus sinensis)

Models (Des)	Parameters	Temperatures		
		30 °C	40 °C	50 °C
GAB	A	9,2304E-01	9,3365 E-01	9,1297 E-01
	B	7,6160 E+01	9,1133 E+01	7,7618 E+01
	C	1,0688 E+01	9,7251	9,1524
	S	2,7245	1,6665	1,2633
	R	0,9951	0,9978	0,9981
	P%	8,8859	6,6305	5,4428
Adam and Shove	A	2,0676	1,9478	1,9418
	B	8,5930 E+01	8,5802 E+01	7,1843 E+01
	D	-2,2229 E+02	-23215 E+02	-1,8045 E+02
	C	2,2256 E+02	2,3013 E+02	1,7729 E+02
	S	3,6502	2,6267	2,1205
	R	0,9934	0,9956	0,9960
	P%	10,4832	9,1633	8,0307
BET	A	9,0809 E-02	1,0438 E-01	7,8962 E-02
	B	4,2106 E+02	3,3124 E+02	4,1608 E+02
	S	3,8324	3,2818	2,9651
	R	0,9878	0,9894	0,9869
	P%	16,8714	15,2190	16,0187
Oswin	A	1,0981 E+05	2,0005 E+05	3,3476 E+05
	B	-3,6598 E+03	-5,0009 E+03	-6,6945 E+03
	C	5,0304 E-01	5,1987 E-01	4,7664 E-01
	S	3,3261	2,6393	2,1348
	R	0,9927	0,9945	0,9946
	P%	61,6922	12,9132	11,6917
Caurrie	A	1,4893	1,3819	1,4384
	B	2,8826	2,9363	2,6789
	S	3,8606	3,3584	2,7271
	R	0,9876	0,9888	0,9890
	P%	12,9299	13,5568	14,9209
Henderson Thompson	A	-2,3711 E-02	-2,1549 E-02	-4,5055 E-02
	B	-3,1574 E+01	-4,1834 E+01	-5,1015 E+01
	S	4,2630	3,7133	3,5223
	R	0,9849	0,9864	0,9815
	P%	18,8119	18,5015	21,8052
Langmuir	A	1,8747 E+04	1,7632 E+04	1,1071 E+04
	B	3,0282 E-03	2,9779 E-03	4,0592 E-03
	S	7,8381	7,2211	5,0607
	R	0,9482	0,9478	0,9615
	P%	33,2468	33,0886	27,1106
Hailwood Horoben	A	3,6336 E+04	-4,1825 E+05	-9,9422 E+06
	B	-4,5576 E+07	-3,0441 E+07	-5,3246 E+02
	C	1,4331 E+09	1,0337 E+09	2,1201 E+04
	S	8,7481	8,0598	5,6443
	R	0,9484	0,9480	0,9617
	P%	66,4627	54,6656	44,2041
Smith	A	3,1961	2,8388	3,3167
	B	2,4870 E+01	2,3541 E+01	1,9735 E+01
	S	3,3497	2,9625	2,3581
	R	0,9902	0,9914	0,9917
	P%	13,3023	13,6515	12,3138

Table 2: Results of fitting of the adsorption isotherms of orange peel (Citrus sinensis)

Models (Ads)	Parameters	Temperatures		
		30 °C	40 °C	50 °C
	A	9,3812E-01	9,5965 E-01	9,3596 E-01
	B	2,3868 E+01	1,7701 E+01	9,5384
GAB	C	9,5242 E+00	7,8164	7,8590
	S	2,8692	1,5550	0,9992
	R	**0,9943**	**0,9988**	**0,9990**
	P%	13,0609	10,6782	5,8800
	A	1,3843	6,1579E-01	9,0990 E-01
	B	7,3700 E+01	7,8599 E+01	5,6225 E+01
Adam and Shove	D	2,1251 E+02	2,3871 E+02	1,7017 E+02
	C	-2,0206 E+02	-2,3592 E+02	-1,5884 E+02
	S	3,1641	1,2986	1,8340
	R	0,9948	0,9988	0,9958
	P%	9,8612	13,4734	12,1449
	A	1,2237 E-01	1,7266 E-01	1,6468 E-01
	B	2,6202 E-02	1,4350 E+02	1,6239 E+02
BET	S	3,1421	1,9956	2,0402
	R	0,9914	0,9956	0,9935
	P%	18,5194	15,8806	17,7861
	A	-1,2817 E+04	1,4808 E+05	-5,3346 E+04
	B	4,2784 E+02	-3,7018 E+03	1,0672 E+03
Oswin	C	5,6308E-01	6,2568E-01	5,9543 E-01
	S	2,9747	1,7158	1,8233
	R	0,9939	0,9974	0,9958
	P%	16,2316	12,0435	13,7109
	A	1,1297	7,1877E-01	7,9670
	B	3,2422	3,5958	3,3450
Caurrie	S	3,2727	2,5742	1,8066
	R	0,9907	0,9927	0,9940
	P%	14,0997	17,4051	12,8461
	A	-4,6271 E-02	-2,1165 E-02	-3,7486 E-02
Henderson Thompson	B	-3,0858 E+01	-4,2106 E+01	-5,1350 E+01
	S	3,3608	2,8825	2,1032
	R	0,9902	0,9908	0,9931
	P%	18,5577	19,7199	19,4680
	A	2,2099 E+04	2,0664 E+04	1,7075 E+04
	B	2,3947 E-03	2,2265 E-03	2,3462 E-03
Langmuir	S	8,3364	7,8757	5,8767
	R	0,9385	0,9296	0,9449
	P%	40,0200	42,4691	39,5787
	A	8,8904 E+04	1,9937 E+05	-1,3209 E+10
	B	-1,2222 E+08	-9,9422 E+07	-3,6614 E+08
Hailwood Horoben	C	4,7511 E+09	3,8518E+09	1,6306 E+10
	S	9,3077	8,7951	6,5612
	R	0,9386	0,9298	0,9451
	P%	35,9069	42,5365	39,5516
	A	1,3912	3,7671E-01	7,4118E-01
	B	2,4354 E+01	2,2200 E+01	1,9278 E+01
Smith	S	3,1770	2,8671	2,0203
	R	0,9913	0,9909	0,9936
	P%	13,9195	16,9309	16,9716

4. Isosteric sorption heats determination:

4.1.1 sorption isosters

The isosteric heat for orange peel is calculated from the desorption and adsorption isosteres figure 6 and 7.

The resulting curves demonstrate that the isosteric heat has higher values for low water content, which illustrates strong binding of water to the substrate, and it becomes negligible compared to the latent heat at high humidity level.

This is because the highly active polar sites of the product are covered with water molecules, which form the monomolecular layer. These account for the rapid fall in isosteric heat at a low-water content in the product.

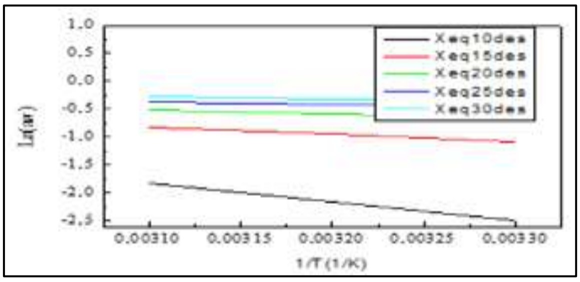

Figure 6: Desorption isosters for orange peel

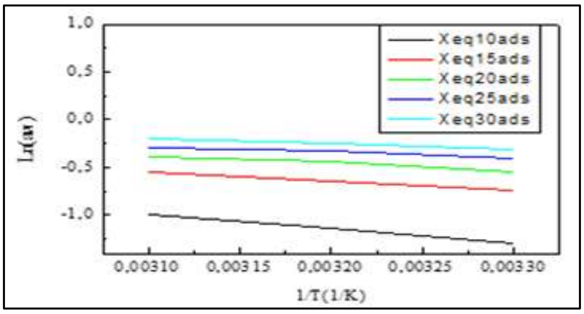

Figure 7: Adsorption isosters for orange peel

4.1.2 Net isosteric heat sorption:

The isosteric heat of adsorption and desorption for different water contents is shown in figures 8 and 9. The isosteric heat of sorption decreases as the water content increases.

Tsami (1991) [25] explains that the high value of sorption heat at low water content is due to the existence of highly active polar sites on the surface of the product. Water molecules form a monomolecular laye.

Using the following relationships, the equilibrium moisture content of the product has been connected with the net isosteric temperatures of water adsorption and desorption from orange peel.

$$Qst = 4,27055 + 193,5037. e^{(-Aw/4,4414)} \quad (5)$$

For desorption where r2=0.9989

$$Qst = 3,4995 + 212,345. e^{(-Aw/4,6018)} \quad (6)$$

For adsorption where r2 =0,99959

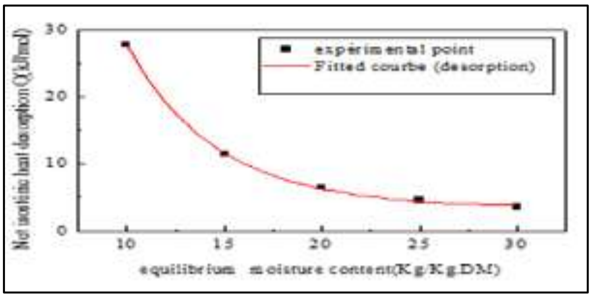

Figure 8: Net isosteric heat desorption of orange peel

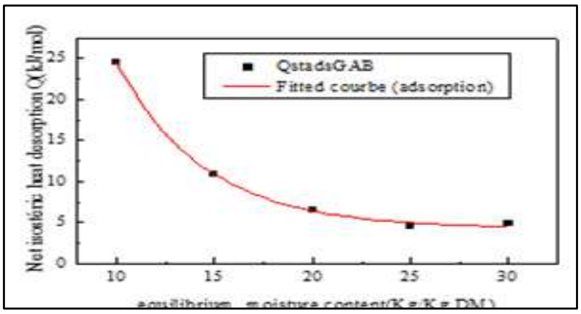

Figure 9: Net isosteric heat adsorption of orange peel

CONCLUSION:

The moisture sorption isotherm of orange peel was determined at 30°C, 40°C, 50°C by a gravimetric method. The

sorption isotherms assume a sigmoid shape.
Equilibrium moisture content decreases with an increase in temperature at constant equilibrium relative humidity and increases with increasing equilibrium relative humidity at constant temperature.
Among the sorption models selected to fit the sorption isotherms, GAB equation seems to be the most appropriate

BIBLIOGRAPHIC REFERENCE:

- Wang, Y. C., Y. C. Chuang, Y. H. Ku. Quantitation of bioactive compounds in citrus fruits cultivated in Taiwan, Food Chem. 102 007) 1163-1171
- Jawad, A, and Langrish, T. A. G. Optimisation of total phenolic acids extraction from mandarin peels using microwave energy: The importance of the Maillard reaction, J. Food Eng., 109 (2012)162-174.
- Gorinstein, S., Martin-Belloso, O. Parck, Y. S. Haruenkit, R. Logek, A. Ciz, M. Libman, I. Traktenberg, S. Comparison of some biochemical characteristics of different citrus fruits, Food Chem., 74 (3) (2001) 309-315.
- Li B. B. Smith, B. Hossain, M. D., M. Extraction of phenolics from citrus peels I. Solvent extraction method, Sep. Purif.Technol., 48 (2006) 182-188.
- Bocco, M. E., Cuvelier Richard, H. Berset, C. Antioxidant activity and phenolic composition of citrus peel and seed extracts, J. Agric. Food Chem., 46 (1998) 2123–2129
- Wang, Y. C., Chuang, Y. C. Hsu, H. W. The flavonoid, carotenoid and pectin content in peels of citrus cultivated in Taiwan, Food Chem. 106 (2008) 277-284.
- Ashok Kumar, K. Narayani, M. Subanthini, A. Jayakumar, M. Antimicrobial Activity and Phytochemical Analysis of Citrus Fruit Peels Utilization of Fruit Waste, Inter. J. Eng. Sci.Technol., 3 (2011) 5417-5421.
- Huang, Y. S., Ho, S. C. Polymethoxy flavones are responsible for the anti-inflammatory activity of citrus fruit peel, Food Chem.,119 (2010) 868-873.
- Moulehi, S. Bourgou I. Ourghemmi, T. Saidani, M. Variety and ripening impact on phenolic composition and antioxidant activity of mandarin (Citrus reticulate Blanco) and bitter orange (Citrusaurantium L.) seeds extracts, Ind. Crops Prod., 39 (2012)74- 80.
- Hosni, K. Zahed, N. Chrif, R. Abid, I. Medfei, W. Kallel, M. Ben Brahim, N. Sebei, H. Composition of peel essential oils from four selected Tunisian Citrus species: Evidence for the genotypic influence, Food Chem., 123 (2010)1098–1104.
- Labuza, T. P., & al. 1968, Sorption phenomena in foods, Food Technology, vol. 22, pp. 263-272.
- Meriem Saidi, Amel Soukaina Cherif, Belkacem Zeghmati, Ezeddine Sediki. Stabilization effects on the thermal conductivity and sorption behavior of earth bricks, Construction and Building Materials 167 (2018) 566–577.doi: 10.1016/j.conbuildmat.2018.02.063
- NF EN ISO 12571. Hygrothermal performance of building materials and products-determination of hygroscopic sorption properties; 2000.
- Thompson.T. L., & al., 1986, Mathematical simulation of corn drying a new model, Transactions of the American Society of Agricultural Engineers, vol. 11, pp. 582-586.
- Pfost & al., 1976, Summarizing and reporting equilibrium moisture data for grains, American Society of Agricultural Engineers, Paper n° 76-3520, St. Josef, MI.
- Oswin, C.R., The kinetics of package life III. The isotherm, J. Chem. Tech. Biotech. 65 (12) (1946) 419–421.https://doi.org/10.1002/jctb.5000651216
- Yassine. M., &al.,2019, Hygrothermal Characterization of Compressed and Cement Stabilized Earth Blocks, international Review of Civil Engineering (I.RE.C.E.), Vol. 10, N. 4 ISSN 2036 - 9913 July 2019
- Halsey. G. Physical adsorption on non-uniform surfaces, J. Chem. Phys16 (1948) 931-937 Smith. SE., The sorption of water vapor by high polymers. J. Am. Chem. Soc 1947; 69: 646.
- Van den Berg.C., Bruin den Berg. C. Bruin. Water activity and its estimation in food systems: theoretical aspects. In: Rockland LB, Stewart GF, editors. Water activity: influences on food quality. New York: Academic Press; 1981. p. 2e61
- Iglesias. H.A. and Chirife. J. Water Sorption Parameters for Food and Food Components, Handbook of food isotherms, Academic Press, New York, 1982a.
- Bellagha.S., Sahli. A., Ben Zid. M. and Farhat. A.,"Desorption isotherms of fresh and osmotically dehydrated apples (Golden delicious) en séminaire "Revue des Energies Renouvelables" in SMSTS'08, 2008, paper 45 – 52, p.59.
- Belghit.A. Kouhila.M. Boutaleb.B.C."Experimental study of drying kinetics byforced convection of aromatic plants", Energy Conversion and Management, vol. 44, pp. 1303–1321, 2000.
- Tsami, E. (1991). Net isosteric heat of sorption in dried fruits. Journal of Food Engineering, 14 (