Equilibrium moisture characteristics of foods – Hysteris effects and isotherm models

Gleichgewichtsfeuchtigkeit von Lebensmitteln – Hysteresiseffekte und Isothermen-Modelle

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Moisture equilibrium data for adsorption and desorption of water from potato starch, egg albumin, wheat gluten, spaghetti and sweet cookies were obtained at 30 °C over the water activity (a_w) range 0.07–0.97, using a static gravimetric method. All materials exhibited the hysteresis phenomenon which was more pronounced in starchy materials (potato starch). B.E.T., G.A.B., Freundlich, Halsey, Henderson, Chung & Pfost and Oswin equations were used for analyzing the sorption data. The analysis indicated that G.A.B., Henderson, Chung & Pfost and Oswin equations fitted the data well over the full range of the isotherms. Monolayer moisture contents for the five substrates were determined from B.E.T. and G.A.B. equations.

Es wurden Wasserdampfsorptions- und Desorptionsdaten für Kartoffelstärke, Eialbumin, Weizenkleber, Spaghetti und Biscuits mit einer gravimetrischen statischen Methode bei 30 °C und in einem Wasseraktivitätsbereich von 0.07 bis 0,97 bestimmt. Alle Produkte zeigten einen Hysteriseffekt zwischen Sorption und Desorption, der in stärkereichen Proben ausgeprägter als in eiweissreichen Proben war. Die Gleichungen nach B.E.T., G.A.B., Freundlich. Halsey, Henderson, Chung & Pfost und Oswin wurden zur Analyse der Sorptionsdaten angewendet. Die Auswertungen zeigten, dass das G.A.B.-Modell sowie die Gleichungen nach Henderson, Chung & Pfost und Oswin einen guten Beschrieb des Sorptionsverhalten im ganzen Wasseraktivitätsbereich ermöglichen. Der Wassergehalt bei Einschichtensorption der fünf Proben wurde mit der B.E.T.- und mit der G.A.B.-Gleichung ermittelt.

Introduction

Water sorption properties are a fundamental characteristic of food materials which influences every aspect of the drying process and the storage stability of the dried product. The majority of the studies in that area have been carried out by constructing the water sorption isotherms. Other techniques were applied only to a lesser extent [1, 2]. Water sorption isotherms describe the mathematical relationship between equilibrium moisture content and water activity at a constant equilibration temperature. They are an important tool in food science because they can be used to predict changes in food stability and to select appropriate packaging materials as well as suitable ingredients.

Moisture sorption hysteresis is the phenomenon according to which different paths exist for adsorption and desorption isotherms. This phenomenon has theoretical and practical implications in foods. The theoretical implications range from general considerations of the irreversibility of the sorption process to the question of validity of thermodynamic functions derived therefrom. The practical implications deal with ease of drying, change in surface structure of the adsorbent by dehydration and the effects of hysteresis on chemical and micorobiological deterioration [3, 4].

Several researchers have reported sorption data for various foods and food constituents. Wolf et al [5] determined the adsorption and desorption isotherms of a variety of dehydrated foods and reported wide differences in the magnitude, shape and extend of hysteresis loops, depending on the type of food and temperature. Van den Berg et al [6] studied the adsorption and desorption behavior of potato starch. They found a reproducible wide hysteresis loop wihich narrowed progressively at water activity below 0.35. Van Twisk [7] studied the sorption isotherms of maize meal. Both adsorption and desorption curves were found to be sigmoid and hysteresis effects were encountered in all cases studied. Bushuk and Winkler [8] determined the sorption isotherms for water vapor on flour, starch, freeze-dried and spray-dried gluten at 27 °C. They found sigmoid isotherms which again show considerable hysteresis persisting over almost the entire water vapor pressure range investigated. Altman and Benson [9] measured sorption isotherms for native and denatured egg albumin. They concluded that the unique type of hysteresis displayed by proteins is attributable to the rearrangements of the molecular framework, induced by water soprtion. Boki and Ohno [10] studied the moisture sorption hysteresis of various starches with different pore size distribution.

Equations for fitting water sorption isotherms in foods are of practical importance in many aspects of food preservation by dehydration, such as for prediction of drying times, predicition of the shelf-life of a dried product in a specific packaging material, evaluation of properties of dry mixes. Several mathematical equations were reported in the literature describing water sorption isotherms of food materials. Chirife and Iglesias [11] compiled and discussed most of these isotherm equations. Iglesias and Chirife [12] also compiled sorption isotherm data for more than 1000 different foods, with mathematical description of over 800 of the reported isotherms. The G.A.B. (Guggenheim – Anderson – De Boer) model is claimed to provide the best equation of food isotherms up to a_w = 0.9 [13] and has been adopted by the European COST 90 bis Group on Water Activity [14].

The objectives of the present study were: a) to obtain equilibrium sorption data for potato starch, egg albumin, wheat gluten, spaghetti and sweet cookies at 30 °C; and b) to test the fit of the sorption data to some well-known sorption isotherm equations (B.E.T., G.A.B., Freundlich, Halsey, Henderson, Chung & Pfost and Oswin) in order to help finding important parameters such as monolayer moisture content.

Materials and Methods

Materials

Potato starch, egg albumin and wheat gluten were purchased from Sigma Chemical Co., USA. Sweet cookies and conventional spaghetti (made of 100% durum wheat semolina) were obtained from a local supermarket.

All chemical reagents used for the preparation of saturated salt solutions were analytical grade. Water used was deionized and distilled.

Methods

Sweet cookies and spaghetti were pulverized before use. All five samples were sieved and 60–80 mesh fractions were used. For measuring the adsorption isotherms, samples were predried in a vacuum oven at 40 °C and kept over P_2O_5 for one week at room temperature. For the measurement of desorption isotherms, samples were hydrated in decanters over distilled water (a_w = 1) at room temperature [15]. Sorption isotherms were determined through equilibration of moist (desorption)

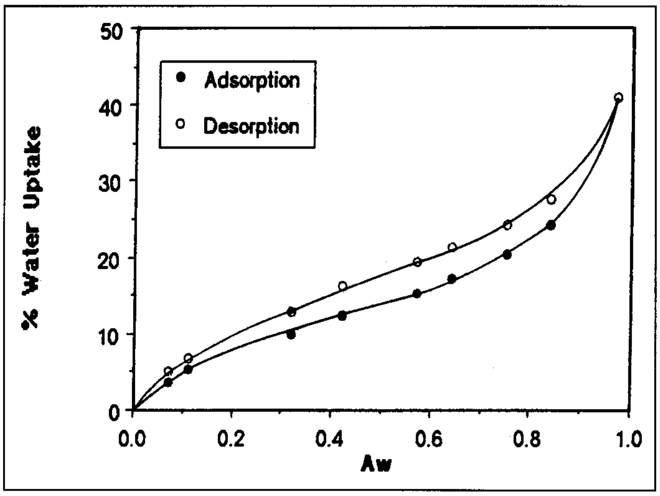

Fig. 1: Sorption Isotherms of Potato Starch at 30 °C

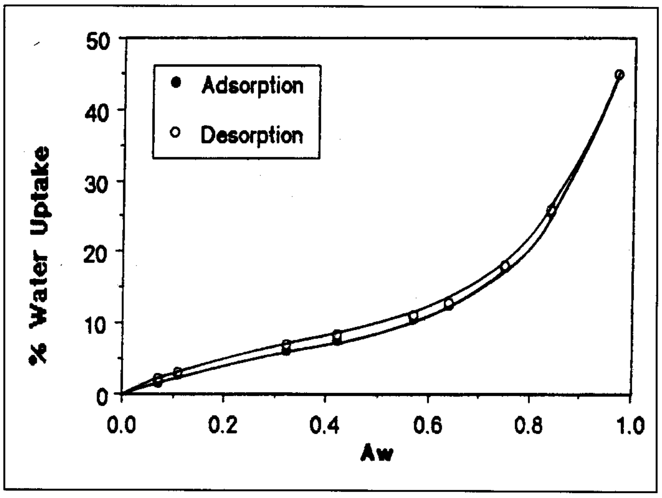

Fig. 2: Sorption Isotherms of Egg Albumin at 30 °C

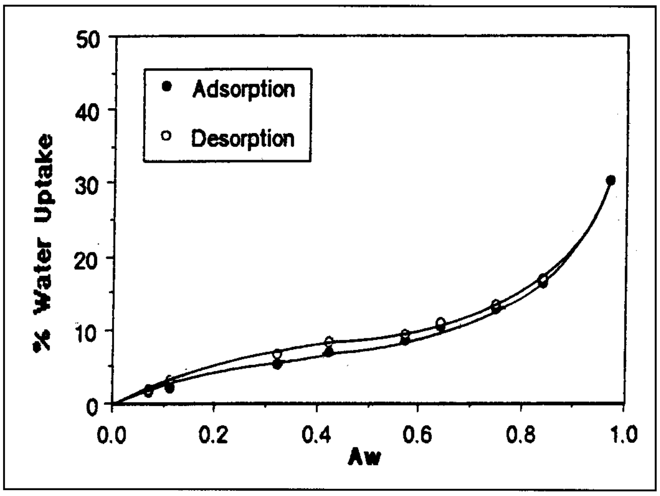

Fig. 3: Sorption Isotherms of Wheat Gluten at 30 °C

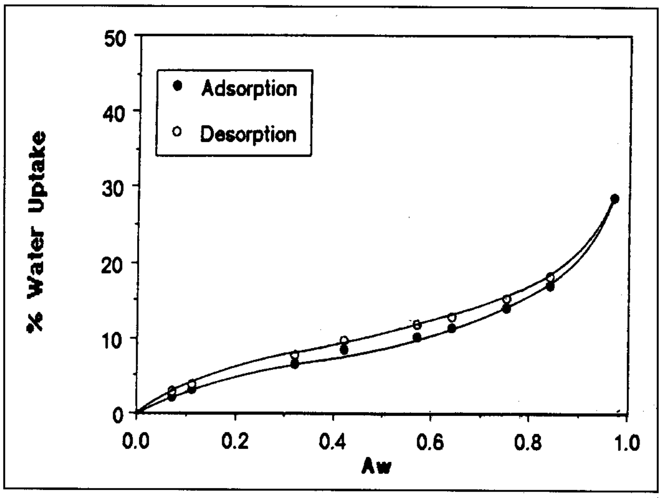

Fig. 4: Sorption Isotherms of Spaghetti at 30 °C

and dried (adsorption) samples over saturated salt solutions of known relative humidities at constant temperature (isopiestic, static method). Nine saturated solutions were prepared corresponding to a range of water activities from 0.07 to 0.97. The relative humidity values for the saturated salt solutions were obtained from reference tables [16]. The saturated solutions were transferred into glass jars in an amount to fill a space of about 2 cm at the bottom. A tripod made of stainless steel was also placed into each jar. Duplicate samples (about 0.5 g) were put into small crucibles of aluminum foil and placed on tripods in the jars which were then tightly closed. Finally, the jars were placed in a constant temperature cabinet held at 30±0.1 °C for equilibration of samples. Under the above conditions the required equilibration time was 3 weeks. Moisture content of the equilibrated samples was determined by the vacuum oven method [17]. The relative deviation in equilibrium moisture contents between the duplicate samples was, on an average, less than 1.5%.

Results and Discussion

Water sorption hysteresis

The sorption isotherms for potato starch, egg albumin, wheat gluten, spaghetti and sweet cookies at 30 °C are, given in **Figs. 1, 2, 3, 4 and 5** respectively. Both, adsorption and desorption isotherms are of sigmoid shape (B.E.T. type II) for all five materials. This form is common for many foods. Each isotherm could be divided into an initial «monolayer region» (water activity levels less than 0.2), an intermediate «multilayer region» (water activity levels of 0.2–0.7) and a final «condensed water region» (water activity levels greater than 0.7).

A hysteresis loop was obtained between the adsorption and desorption branches. This actually may indicate non-equilibrium at the end of the sorption experiments although the reproducibility of the isotherms both in adsorption and desorption was very good. There were considerable differences in the extent of hysteresis effects obtained for the various substrates. For potato starch (representing starchy materials) a significant hysteresis effect (large hysteresis loop) particularly at the multilayer and capillary condensation region was observed **(Fig. 1)**. In case of proteinceous substrates (egg albumin and wheat gluten) **(Figs. 2, 3)** hysteresis began in the capillary condensation area, at an a_w-value of about 0.80. The total hysteresis was small and was fairly evenly distributed along the isotherm, except for a slight maximum at an a_w-value of about 0.30 in the case of gluten **(Fig. 3)**. As for spaghetti, a product containing both starch and protein, a moderate hysteresis loop was obtained with a maximum at an a_w-value of 0.40, which ist within the multilayer region **(Fig. 4)**. In sweet cookies, which are a sugar-containing product, a moderate hysteresis occurred, predominantly in the monomolecular region. No hysteresis was observed above a water activity of 0.60 **(fig. 5)**.

The water sorption hysteresis for starch may be interpreted either by the capillary condensation theory, according to which a vapor condenses to a liquid in pores, or by

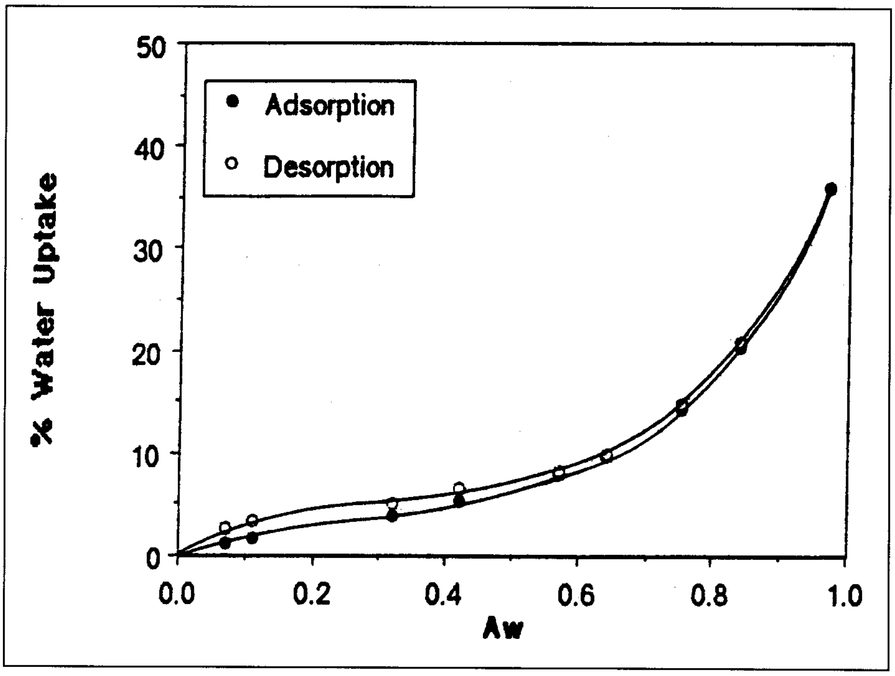

Fig. 5: Sorption Isotherms of Sweet Cookies at 30 °C

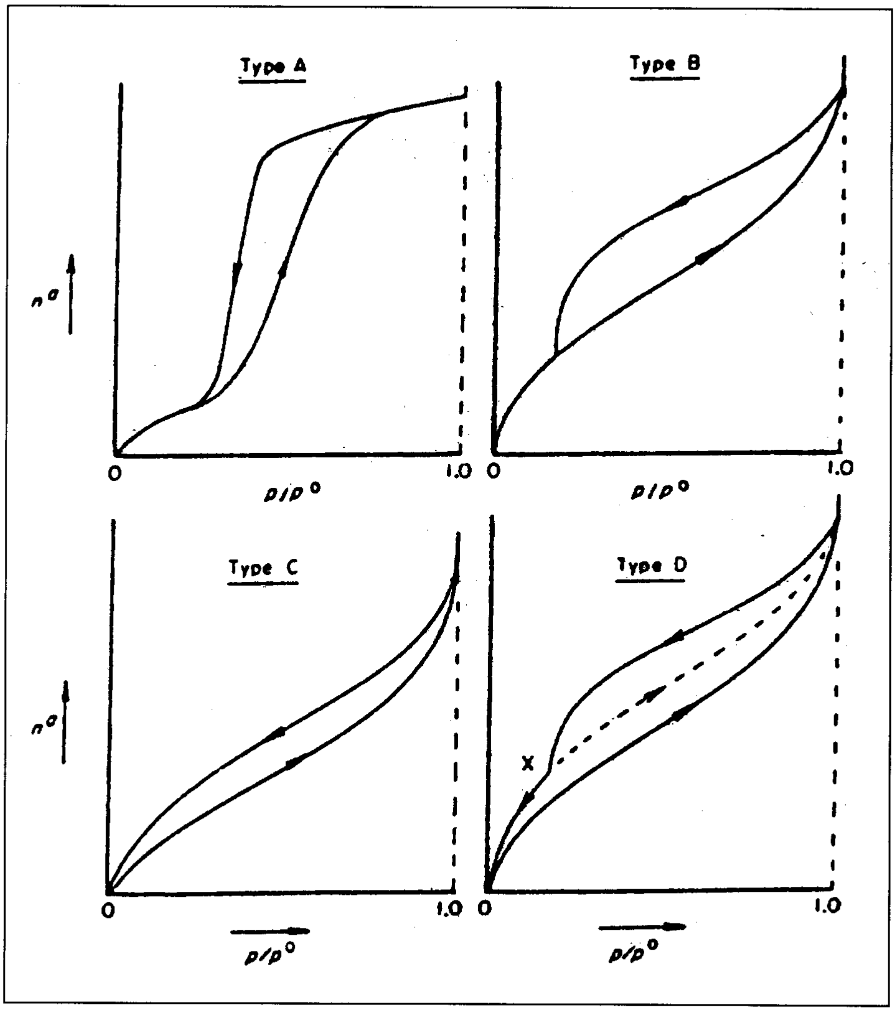

Fig. 6: Types of hysteresis according to the classification of Everett (23)

deformation of starch granules due to moisture sorption and swelling associated with starch granules and bound water [3, 5]. In a sweeling polymer, a large sorptive and swelling capacity associated with a weakly bound polymer matrix and weakly bound water, leads to a small hysteresis loop. In the opposite case, a small sorptive and swelling capacity associated with a tightly bound matrix and strongly bound water leads to a large hysteresis [4]. According to some investigators [10, 18] no relation between the magnitude of the hysteresis loop and the strength of moisture-to-starch binding has been indicated. They claimed that the differences in the hysteresis loops for various starches can be explained by differences in the pore size distribution of them. However, experiments carried out by other investigators [6] showed that potato starch is a non-porous material and therefore capillary condensation cnnot play a significant role in water binding.

Concerning high-protein foods, a small or moderate hysteresis is usually observed beginning at high water activity, in the capillary condensation region, and extending over the rest of the isotherms to zero water activity [4]. In both adsorption and desorption, the isotherms retain the characteristic sigmoid shape for proteins. Hysteresis in proteins may be attributed to incomplete conformational changes occurring upon addition and removal of water, to an incomplete process of intermolecular phase annealing and to incomplete phase change if two different protein phases are present [19].

In high-sugar foods, hysteresis is more pronounced in the lower moisture content region, below the first inflection point of the sorption isotherm. Although the total hysteresis is relatively large, there is usually no hysteresis above water activity 0.50–0.60. The water activity below which a significant hysteresis effect occurs is inversely proportional to the sugar content of foods [4, 5, 20, 21]. This can be attributed to the absence of capillarity in the surface of foods [5] as well as to the dissolution of sugars, which is more pronounced at high water activities [22].

In general, the several causes of sorption hysteresis are impurities on the surface of the adsorbent, the presence of some irreversible water phase change, irreversible swelling of the adsorbent, intermolecular phase annealing and a capillary condensation-evaporation process in small pores. In nature, hysteresis may be considered as a built-in protective mechanism against extremities such as loss of water due to a dry atmosphere, frost damage and freezer burn. Figure 6 shows four types of hysteresis according to the classification of Everett [23]. In type A the loop occurs over a limited range of relative pressures. In type B the loop extends from the saturation vapor pressure down to a well-defined closure point, which is characteristic mainly of the kind of the vapor adsorbed. In type C the loop extends over the entire range of vapor pressure. In type D, which is a mixture of types B and C, the desorption curve follows the pattern of type B loop but before meeting the adsorption curve it bends away downward to the zero vapor pressure as in type C. The hysteresis loops that were obtained in the present experiments could be classified in type C. In general,

Sample	Applicable range aw	Parameter constants Vm	C	Regression Coefficient
Potato Starch (A)	0.07–0.64	0.070	21.01	0.98
Potato Starch (D)	0.07–0.64	0.083	32.21	0.97
Egg Albumin (A)	0.07–0.64	0.050	7.56	0.99
Egg Albumin (D)	0.07–0.64	0.051	9.60	0.99
Wheat Gluten (A)	0.07–0.64	0.042	8.71	0.98
Wheat Gluten (D)	0.07–0.64	0.043	19.37	0.95
Spaghetti (A)	0.07–0.57	0.050	12.64	0.97
Spaghetti (D)	0.07–0.57	0.054	18.95	0.98
Sweet Cookies (A)	0.07–0.64	0.039	5.44	0.99
Sweet Cookies (D)	0.07–0.64	0.040	22.20	0.99

(A): Adsorption, (D): Desorption

Table 1: Analysis of water sorption data according to B.E.T. equation

Sample	Applicable range aw	Parameter constants Vm	C	k	Regression Coefficient
Potato Starch (A)	0.07–0.97	0.090	10.54	0.78	0.98
Potato Starch (D)	0.07–0.97	0.128	11.78	0.70	0.97
Egg Albumin (A)	0.07–0.84	0.059	6.02	0.93	0.97
Egg Albumin (D)	0.07–0.84	0.060	7.04	0.92	0.97
Wheat Gluten (A)	0.07–0.84	0.059	5.91	0.78	0.93
Wheat Gluten (D)	0.07–0.84	0.074	7.57	0.68	0.92
Spaghetti (A)	0.07–0.84	0.074	8.25	0.71	0.99
Spaghetti (D)	0.07–0.84	0.079	11.18	0.68	0.99
Sweet Cookies (A)	0.07–0.84	0.041	5.19	0.97	0.98
Sweet Cookies (D)	0.07–0.84	0.043	19.76	0.93	0.99

(A): Adsorption, (D): Desorption

Table 2: Analysis of water sorption data according to G.A.B. equation

Sample	Applicable range aw	Parameter constants k	n	Regression Coefficient
Potato Starch (A)	0.07–0.84	0.253	1.37	0.98
Potato Starch (D)	0.07–0.84	0.287	1.51	0.99
Egg Albumin (A)	0.07–0.75	0.189	1.11	0.98
Egg Albumin (D)	0.07–0.75	0.190	1.17	0.98
Wheat Gluten (A)	0.07–0.75	0.150	1.18	0.99
Wheat Gluten (D)	0.07–0.75	0.156	1.33	0.99
Spaghetti (A)	0.07–0.84	0.171	1.31	0.99
Spaghetti (D)	0.07–0.84	0.176	1.48	0.99
Sweet Cookies (A)	0.07–0.75	0.148	1.03	0.97
Sweet Cookies (D)	0.07–0.75	0.153	1.30	0.92

(A): Adsorption, (D): Desorption

Table 3: Analysis of water sorption data according to Freundlich equation

the types of changes encountered upon adsorption and desorption will depend on a) the initial state of the sorbent (amorphous versus crystalline), b) the transitions taking place during adsorption, c) the final water activity adsorption point and d) the speed of desorption. With regard to (c) and (d), if the saturation point has been reached and the material has gone into solution, rapid desorption may preserve the amorphous state due to supersaturation. In conclusion, several theories have been proposed to interprete the phenomenon of hysteresis. At present, no theory has given a complete penetration into the several mechanisms responsible. The principal factors affecting hysteresis are the composition of the product, its drying temperature, storage time and temperature, and the number of succesive adsorptions and desorptions. Thus, hysteresis is an important feature of the water sorption behaviour of the different foods, and it is very significant for the quality characteristics of foodstuffs, providing information which is not available from consideration of either the adsorption or desorption isotherm alone.

Fitting of sorption data to various isotherm equations

In order to derive a simple relation between water uptake and water activity experimental data were fitted to some of the many equations published in the literature. Among the two parameters equations those of B.E.T., Freundlich, Halsey, Henderson, Chung & Pfost and Oswin were selected, and among those of three parameters the G.A.B. equation was chosen. From B.E.T. and G.A.B. equations monolayer values were computed.

B.E.T. Isotherm

One of the most popular food isotherm equations is the B.E.T. This equation provides the value of monolayer moisture content which is an important parameter in food deterioration studies. A number of investigators [24, 25] noticed that knowledge of water uptake at the monolayer value is of great importance because it is the level of moisture content at which dehydrated foods have otpimum storage stability because of the protective effect of water against oxygen adsorption and interaction of adjacent polar groups. The B.E.T. model is known to hold for water activities up to about 0.5. It is expressed by equation 1:

$$a_w / (1-a_w) \cdot V = 1 / V_m\text{-}C + a_w \cdot (C-1) / V_m \cdot C \quad \text{Eqn [1]}$$

where a_w : water activity
V : water uptake, (kg/kg)
V_m : monolayer moisture content, (kg/kg)
C : sorption constant related to the heat of adsorption of the first layer.

The values of the B.E.T. constants for adsorption and desorption are given in **Table 1** together with the correlation coefficients.

G.A.B. Isotherm

In recent years, the most widely accepted model for sorption isotherms has been the

G.A.B. model. It is considered to be an extension of the B.E.T. multimolecular localized homogeneous adsorption model. It is reported as giving a remarkable fit over a wide range of water activity (up to 0.9) and a very good evaluation for the amount of water tightly bound by the primary adsorption sites [26–28]. The G.A.B. equation as applied to water vapor sorption can be written as:

$$V / V_m = C \cdot K \cdot a_w / (1\text{-}Ka_w) \cdot (1\text{-}Ka_w + CKa_w) \qquad \text{Eqn [2]}$$

where C: Guggenheim's constant
K: correction factor.

Equation [2] can be transformed into equation [3].

$$a_w / V = A \cdot a_w^2 + B \cdot a_w + \Gamma \qquad \text{Eqn [3]}$$

where $A = K(1\text{-}C) / V_mC$ Eqn [4]

$B = (C\text{-}2) / V_mC$ Eqn [5]

$\Gamma = 1 / V_mCK$ Eqn [6]

A plot of a_w/V vs a_w gives a parabolic curve. Using equations [4], [5], [6] parameters V_m, C an K can be calculated **(Table 2).**

It was observed that values for monolayer moisture content computed from B.E.T. and G.A.B. equations were different in the two processes, adsorption and desorption. More specifically, V_m values computed from desorption data were always higher than those obtained from adsorption data. Van den Berg et al. [6] observed the same trend for starch. This can be explained by the faxt that the equilibrium moisture content is higher at a particular water activity for desorption curve than for adsorption. It was also observed that the monolayer values calculated from the GAB equation were higher than those calculated from the B.E.T. equation. Labuza et al [29] also reported greater magnitude of the G.A.B. monolayer value than the B.E.T. monolayer value for fish flour and corn meal.

Potato starch exhibited the highest V_m values due to its hydrophilic nature. Spaghetti and proteins exhibited intermediate V_m values. Sweet cookies gave the lowest V_m values, and this fact can be attributed to the considerable amount of crystalline sugar they contain.

Freundlich Isotherm

This model is important for explaining the sorption behaviour of heterogeneous surfaces such as those of most foods. It has also been successfully applied to various foodstuffs [30, 31]. It is expressed by equation [7]:

$$V = k \cdot a_w^{1/n} \qquad \text{Eqn [7]}$$

or $$\log V = \log k + 1/n \cdot \log a_w \qquad \text{Eqn [8]}$$

Sample	Applicable range aw	Parameter constants $A \times 10^{-2}$	B	Regression Coefficient
Potato Starch (A)	0.07–0.57	8.22	1.10	0.97
Potato Starch (D)	0.07–0.57	9.68	1.14	0.97
Egg Albumin (A)	0.07–0.64	7.11	0.94	0.97
Egg Albumin (D)	0.07–0.64	6.45	1.00	0.97
Wheat Gluten (A)	0.07–0.64	5.58	0.97	0.97
Wheat Gluten (D)	0.07–0.64	4.54	1.10	0.99
Spaghetti (A)	0.07–0.64	4.59	1.12	0.95
Spaghetti (D)	0.07–0.64	3.68	1.27	0.96
Sweet Cookies (A)	0.07–0.84	4.42	0.98	0.98
Sweet Cookies (D)	0.07–0.84	2.03	1.36	0.99

(A): Adsorption, (D): Desorption

Table 4: Analysis of water sorption data according to Halsey equation

Sample	Applicable range aw	Parameter constants A	B	Regression Coefficient
Potato Starch (A)	0.07–0.97	17.63	1.68	0.99
Potato Starch (D)	0.07–0.97	19.45	1.89	0.99
Egg Albumin (A)	0.07–0.97	11.32	1.23	0.99
Egg Albumin (D)	0.07–0.97	12.21	1.29	0.99
Wheat Gluten (A)	0.07–0.97	21.22	1.37	0.99
Wheat Gluten (D)	0.07–0.97	27.23	1.54	0.99
Spaghetti (A)	0.07–0.97	29.79	1.60	0.99
Spaghetti (D)	0.07–0.97	38.96	1.79	0.99
Sweet Cookies (A)	0.07–0.97	12.98	1.15	0.99
Sweet Cookies (D)	0.07–0.97	27.31	1.55	0.94

(A): Adsorption, (D): Desorption

Table 5: Analysis of water sorption data according to Henderson equation

where k, n: constants related to the sorptive efficiency of the sorbent.

Constant k is known as the sorptive capacity of the material. Plot of logV vs $\log a_w$ permits the calculation of k and n. **(Table 3).** Justification of values for sorptive capacity (a constant analogous to V_m constant of B.E.T. equation) is the same to that given for the B.E.T equation.

Halsey Isotherm

Halsey [32] developed the following equation to provide an expression for condensation of multilayers at a relatively large distance from the surface:

$$a_w = \exp(-A \cdot V^{-B}) \qquad \text{Eqn [9]}$$

or $$\ln V = [\ln A - \ln(-\ln a_w)] / B \qquad \text{Eqn [10]}$$

where A, B: constants.

Plots of lnV vs $\ln(-\ln a_w)$ permit the calculation of A and B **(Table 4).**

Equation [9] was developed by Halsey on theoretical ground as a criticism of the B.E.T. theory. Halsey stated that the magnitude of the parameter B characterizes the type of interaction between the vapor and the solid. If B is large, the attraction of the solid for the vapor is very specific and does not extend far from the surface; when B is smaller the forces are more typical Van der Waals and are not to act at a greater distance. This eqauation was shown by Halsey to be a good representation of adsorption data that conform to the B.E.T. type I, II and III shapes.

Henderson Isotherm

On of the most widely used models relating water activity and amount of water sorbed is Henderson's equation [33]. This empirical equation may be written as:

$$1\text{-}a_w = \exp(-A \cdot V^{B}) \qquad \text{Eqn [11]}$$

where A, B: constants.

Equation [11] may be written:

$$\ln V = \{\ln[-\ln(1\text{-}a_w)] - \ln A\} / B \qquad \text{Eqn [12]}$$

so a plot of lnV vs ln[-ln(1-aw)] permits the calculation of A and B **(Table 5).**

Henderson [33] recognized that the Gibb's adsorption theory, which was used in the derivation of his equation, has not been completely substantiated by experiment on moisture sorption on starch. He also noted that there was no relation between the magnitude of constants (A and B) of Henderson's equation and the properties of the material.

Chung & Pfost Isotherm

Based directly upon an assumption that the change in free energy for sorption is related to moisture content, Chung and Pfost [45] presented a model of the form:

$$\ln a_w = -A \cdot \exp(-BV) \qquad \text{Eqn [13]}$$

or

$$V = [\ln A - \ln(-\ln a_w)] / B \qquad \text{Eqn [14]}$$

where A, B: constants.

A plot of V vs $\ln(-\ln a_w)$ permits the calculation of A and B **(Table 6).**

The constants A and B of Chung & Pfost equation were dependent on temperature and type adsorbent [34].

Boki and Ohno [18] proposed that the magnitude of constants in Henderson's and Chung & Pfost's equations are related to the stability of microporous structure of the starch during moisture sorption. (The higher the value of constant, the more stable the microporous structure.)

Oswin Isotherm

Oswin [35] presented an equation primarily to solve a packaging problem. This equation is a mathematical series expansion for isigmoid shaped curves, and may be written as follows:

$$V = A \cdot [a_w / (1-a_w)]^B \qquad \text{Eqn [15]}$$

or

$$\ln V = \ln A + B \ln[a_w / (1-a_w)] \qquad \text{Eqn [16]}$$

where A, B: constants.

A plot of lnV vs $\ln[a_w / (1-a_w)]$ permits the calculation of A and B **(Table 7).**

G.A.B., Henderson, Chung & Pfost and Oswin equations fitted well the experimental data in the whole water ativity range tested. B.E.T., Freundlich and Halsey equations fitted well only in the lower and intermediate range of water activity.

	Applicable range	Parameter constants		Regression
Sample	aw	A	$B \times 10^{-2}$	Coefficient
Potato Starch (A)	0.07–0.97	3.93	12.02	0.99
Potato Starch (D)	0.07–0.97	5.59	12.50	0.99
Egg Albumin (A)	0.07–0.97	2.24	10.28	0.96
Egg Albumin (D)	0.07–0.97	3.06	10.37	0.97
Wheat Gluten (A)	0.07–0.97	2.69	15.69	0.98
Wheat Gluten (D)	0.07–0.97	3.16	16.31	0.98
Spaghetti (A)	0.07–0.97	3.62	17.21	0.99
Spaghetti (D)	0.07–0.97	4.33	17.69	0.99
Sweet Cookies (A)	0.07–0.97	2.07	12.34	0.96
Sweet Cookies (D)	0.07–0.97	2.48	13.30	0.95

(A): Adsorption, (D): Desorption

Table 6: Analysis of water sorption data according to Chung & Pfost equation

	Applicable range	Parameter constants		Regression
Sample	aw	$A \times 10^{-2}$	$B \times 10^{-2}$	Coefficient
Potato Starch (A)	0.07–0.84	13.36	45.12	0.99
Potato Starch (D)	0.07–0.84	15.99	40.61	0.98
Egg Albumin (A)	0.07–0.97	8.77	54.62	0.98
Egg Albumin (D)	0.07–0.97	9.23	52.29	0.98
Wheat Gluten (A)	0.07–0.84	7.42	54.66	0.99
Wheat Gluten (D)	0.07–0.84	8.30	47.95	0.97
Spaghetti (A)	0.07–0.84	8.76	46.96	0.98
Spaghetti (D)	0.07–0.84	9.71	41.76	0.99
Sweet Cookies (A)	0.07–0.97	6.45	58.83	0.98
Sweet Cookies (D)	0.07–0.97	8.12	44.75	0.98

(A): Adsorption, (D): Desorption

Table 7: Analysis of water sorption data according to Oswin equation

References

[1] Gurme, A. G., Schmidt, J. S. and Steinberg, P. M. Mobility and activity of water in casein. Model systems as determined by ^{2}H NMR and sorption isotherms. Journal of Food Science, 55, 430–433 (1990).

[2] Kuntz, I. D. and Kauzmann, W. Hydration of proteins and polypeptides. Advances in Protein Chemistry, 28, 239–345 (1974).

[3] Kapsalis, J. G. Moisture sorption hysteresis. In: Water Activity: Influences on Food Quality, Rockland, L. B. and Stewart, G. F. (eds). Academic Press, New York (1981).

[4] Kapsalis, J. G. Influences of hysteresis and temperature on moisture sorption isotherms. In: Water Activity: Theory and Applications to Food, Rockland, L. B. and Beuchat, L. R. (eds). Marcel Dekker Inc. New York (1987).

[5] Wolf, M., Walker, J. E. and Kapsalis, J. G. Water vapor sorption hysteresis in dehydrated foods. Journal of Agricultural and Food Chemistry, 20 (5), 1073–1077 (1972).

[6] Van den Berg, C., Kapel, S. F., Welbring, G. A. J. and Wolters, J. Water binding by potato starch. Journal of Food Technology, 10, 589–602 (1975).

[7] Van Twisk, P. The sorption isotherms of maize meal. Journal of Food Technology, 4, 75–82 (1969).

[8] Bushuk, W. and Winkler, C. A. Sorption of water vapor of wheat flour, starch and gluten. Cereal Chemistry, 34 (2), 73–86 (1957).

[9] Altman, R. L. and Benson, S. W. The effect of water upon the rate of heat denaturation of egg albumin. Journal of the Americal Chemical Society, 82, 3852–3857 (1960).

[10] Boki, K. and Ohno, S. Moisture sorption hysteresis in Kudzu starch an sweet potato starch. Journal of Food Science, 56 (1), 125–127 (1991).

[11] Chirife, J. and Iglesias, H. A. Equations for fitting water sorption isotherms of foods: Part I – A review. Journal of food Technology, 13, 159–174 (1978).

[12] Iglesias, H. A. and Chirife, J. In: Handbook of Food Isotherms: Water Sorption Parameters for Food and Food Components. Academic Press, New York (1982).

[13] Van den Berg, C. Development of

B.E.T.-like models for sorption of water on foods theory and relevance. In: Properties of Water in Foods, Simatos, D. and Multon, J. L. (eds). Martinus Nijhoff Publishers, Dordrecht (1985).

[14] Bizot, H. Using the G.A.B. model to construct sorption isotherms. In: Physical Properties of Foods, Jowitt, R., Escher, F., Hallstrom, B., Meffert, H. F. T., Spiess, W. E. L. and Vos, G. (eds). Applied Science Pubishers, London (1983).

[15] Saravacos, G. D., Tsiourvas, D. A. and Tsami, E. Effect of temperature on the water adsorption isotherms of sultana raisins. Journal of Food Science, 51 (2), 381–383 (1986).

[16] O'Brien, M. A. The control of humidity by saturated salt solutions. Journal of Scientific Instruments, 25, 73–76 (1948).

[17] Karmas, E. Techniques for measurement of moisture content of foods. Food Technology, 34 (4), 52–59 (1980).

[18] Boki, K. and Ohno, S. Equilibrium isotherm equations to represent moisture sorption on starch. Journal of Food Science, 56 (4), 1106–1110 (1991).

[19] Bryan, W. P. Thermodynamic models for water-protein sorption hysteresis. Biopolymers, 26, 1705–1716 (1987).

[20] Chinachoti, P. and Steinberg, M. P. Moisture hysteresis is due to amorphous sugar. Journal of Food Science, 51 (2), 453–455 (1986).

[21] Bolin, H. R. Relation of moisture to water activity in prunes and raisins. Journal of Food Science, 45, 1190–1192 (1980).

[22] Tsami, E., Marinos-Kouris, D. and Maroulis, Z. B. Water sorption isotherms of raisins, currants, figs, prunes and apricots. Journal of Food Science, 55 (6), 1594–1597 (1990).

[23] Everett, D. H. Adsorption hysteresis. In: The Solid-Gas Interface, Flood, E. A. (ed). Marcel Dekker Inc., New York (1967).

[24] Salwin, H. Moisture levels required for stability in dehydrated foods. Food Technology, 17, 34–41 (1963).

[25] Aguerre, J. R. Suarez, C. and Viollaz, E. P. Some aspects derived from B.E.T. theory and their relation with food conservation. Lebensmittel-Wissenschaft und -Technologie, 19, 328–330 (1986).

[26] Van den Berg, C. Description of water activity of foods for engineering purposes by means of the GAB model of sorption. In: Engineering and Food, Vol. 1, Mc Kenna, B. M. (ed). Elsevier Appl. Sci. Publ., London (1984).

[27] Wolf, M., Spiess, W. E. L. and Jung, G. Standarization of isotherm measurements. In: Properties of Water in Foods, Simatos, D. and Multon, J. L. (eds). Martinus Nijhoff Publ., Dordrecht (1985).

[28] Schar, W. and Ruegg, M. The evaluation of GAB constants from water vapor sorption data. Lebensmittel-Wissenschaft und -Technologie, 18, 225–229 (1985).

[29] Labuza, T. P., Kaanane, A. and Chen, J. Y. Effect of temperature on the moisture sorption isotherms and water activity shift of two dehydrated foods. Journal of Food Science, 50, 385–391 (1985).

[30] Smith, D. S., Mannheim, C. H. and Gilbert, S. G. Water sorption isotherms of sucrose and glucose by inverse gas chromatography. Journal of Food Science, 46, 1051–1053 (1981).

[31] Demertzis, P. G. and Kontominas, M. G. Study of water sorption of egg powders by inverse gas chromatography. Zeitschrift für Lebensmittel Untersuchung und Forschung, 186, 213–217 (1988).

[32] Halsey, G. Physical adsorption on non-uniform surfaces. Journal of Chemical Physis, 16, 931–937 (1948).

[33] Henderson, S. M. A basic consept of equilibrium moisture. Agriculture Engineering, 2, 29–32 (1952).

[34] Chung, D. S. and Pfost, H. B. Adsorption and desorption of water vapor by cereal grains and their products. Part II: Development of the general isotherm equation. Transactions of the American Society for Agricultural Engineers, 10 (4), 552–555 (1967).

[35] Oswin, C. R. the kinetics of package life. III. Isotherm. Journal of the Society of Chemical Industry, 65, 419–421 (1946).

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