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The determination of moisture sorption isotherms and the isosteric heat of sorption for irradiated and non-irradiated durum wheat

Moussaoui Haytem[a*], Idlimam Ali[a], Lamharrar Abdelakder[a], Kouhila Mounir[a], Bahammou Younes[a], Mouhib Mohamed[b], Amamou Ali[c]

[(a)] Team of Solar Energy and Medicinal Plants, Teacher's Training College, Cadi Ayyad University, BP 2400 Marrakesh, Morocco

[(b)] Regional Centre for Agricultural Research CRRA, Ionization Station Boukhalef, Tanger, Morocco

[(c)] National Institute of Agronomic Research, B.P 589, Settat, Morocco

** Corresponding author:*
haytem.moussaoui@gmail.com
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Abstract

Durum Wheat is deemed of as one of the most important agricultural elements in the food system. Gamma irradiation treatment proves to be an efficient technique to decontaminate cereals so that we can ensure their hygienic quality during conservation. This paper seeks to study the hygroscopic behavior of irradiated and non-irradiated durum wheat at three temperatures 30 °C, 40 °C and 50 °C using the static gravimetric method. Furthermore, modeling the relationship between the water activity and the equilibrium moisture content has been conducted through several models. GAB and Halsey were selected as convenient models that represent moisture sorption isotherms data for durum wheat. The net isosteric heat of sorption, the specific surface area of sorption was calculated via several equations including the Marquardt–Levenberg algorithm. As a result, the study of the samples reveals that the ionization at a low dose affects the moisture sorption of durum wheat.

Keywords: *Irradiation, Durum wheat, Sorption isotherms, Optimal water activity, GAB model, Net isosteric heat*

1. Introduction

Cereal crops are considered as a nutritional base in human nutrition throughout the history of civilizations. Wheat is a crucial crop in the cultivation of cereals worldwide. Its production over the period between 2010 and 2014 has been quantified by an average of 690 million tons [1]. Research on wheat shows that it contains a variety of phytochemicals, dietary fiber, minerals, amino acids, and vitamins. It is also deemed as an essential source of calories [1, 2]. This grain has several groups; the most commonly used and consumed are durum wheat (*Triticum durum*) and common wheat (*Triticum æstivum*). The conservation of durum wheat is an essential element in the cereal science research. Indeed, the control of this process has become indispensable because it affects the three main human activities: food, agriculture, and trade. While preserving wheat seeds, several quality characters like moisture content, seed germination, and seed discoloration are likely to vary. This variation is attributed to a number of factors [3]. The humidity and the temperature are considered major factors that affect the quality of grain wheat [4,5].It is taken for granted that water represents a primordial constituent of food. Therefore, water activity directly determines the chemical, physical and microbiological properties of a large number of substances as Rockland and Beuchat (1987) [6] point out. What's more, water is a critical factor that is responsible for food conservation. Rockland and Beuchat report that water activity is always situated between zero and one. Indeed, if the binding forces are intense, this activity tends to reach zero; on the other hand, if the water approaches the free state, this activity often drifts towards one. The irradiation gamma treatment of food is an innovative efficient technique that seek to decontaminate food product, ameliorate food safety and prolong shelf life [7]. While exposing the food product to a predefined dose of radiation [8, 9]. The amount of microbes, bacteria, viruses and insects are decreased. It has been reported that the commercial-scale use of food processing irradiation has been fruitful and successful in many areas worldwide. According to Aziz et al. (2006) [10], the gamma irradiation doses within the range of 0.2–1.0 kGy in cereals prove to be an adequate configuration that evidently controls insect infestation without essentially affecting the nutritional quality of grains.Moreover, other studies show that the gamma irradiation and water activity are the main factors that control the quality of food product preservation [11]. In this respect, investigating the impact of the irradiation gamma on the water activity of durum wheat is of a paramount significance in the present study.Durum wheat is one of the most commercial food products of the global agro-food industry. To handle the logistic of this commercialization, the conservation process of the product is necessary. The gamma irradiation is an innovative treatment technique to decontaminate the food product. This method is used in order to preserve the quality and the safety of durum wheat. The objective of this work was to study and to compare the hygroscopic behavior of the treated and untreated durum wheat. In order to study the effect of ionization on the hygroscopic behavior of durum wheat as well as analyze the relation between water activity and the product moisture content, it is necessary to rely on moisture sorption. This phenomenon actually exhibits to what extent the product is sensitive to changes in moisture. In other words, it determines the stability of the product during storage and drying process [12].Along with probing the moisture sorption behavior, the modeling of sorption isotherms is a necessary technique that enables us to predict the adequate sorption characteristics that occur during the conservation process. Furthermore, modeling helps study the Thermophysical properties of the durum wheat [13].It is worth mentioning that the determination of the thermodynamic properties of grains is also of extreme importance in this study. Indeed, the knowledge of the heat of sorption and the specific surface area of sorption provides utile information about the different energies that are required in the interaction between the water and wheat during the sorption phenomena [14].In this paper, the emphasis has been laid on studying and comparing the hygroscopic behavior of irradiated and non-irradiated durum wheat as well as their thermodynamic properties. To attain this objective the study depends on several techniques such as sorption isotherms, sorption hysteresis, modeling, and the Thermophysical characteristics of wheat.

2. Materials and methods

2.1. Materials and experimental protocol

In order to reach the hygroscopic equilibrium of these samples, the static gravimetric method and the salt solution method were needed. In this respect, six watertight jars with a sample holder for each one is needed along with the following salt solutions (KOH, ($MgCl_2$, $6H_2O$), K_2CO_3, $NaNO_3$, KCl, and ($BaCl_2$, $2H_2O$)) placed in an adjustable temperature laboratory oven in order to provide a constant relative humidity. These relative humidity values of saturated salt solutions were obtained from the study of Young (1967) [15] and Greenspan (1977) [16]. These solutions allow us to obtain relative humidity ranging from 5% to 90% [17] (Table 1). Moreover, an electronic balance precisely the one characterized by 0.0001g value were used in the experiment.

Table 1. *Standard values of the water activities of the six saturated salts used for the determination of sorption curves.*

Salt solutions	Water activities aw		
	30°C	40°C	50°C
KOH	0.0738	0.0626	0.0572
$MgCl_2$, $6H_2O$	0.3238	0.3159	0.3054
K_2CO_3	0.4317	0.4230	0.4091
$NaNO_3$	0.7275	0.7100	0.6904
KCl	0.8362	0.8232	0.8120
$BaCl_2$, $2H_2O$	0.8980	0.8910	0.8823

Figure A.1 illustrates the experimental setup used. It consists of an incubator filled with six jars each containing a different saline solution (Figure B.1) each sample is put in a small bottle and placed on a tripod placed in each jar. The jars must be tightly closed so that the partial pressure of the water vapor remains constant throughout the experiment. In jars where the air humidity is high (saturated solutions of NaNO3, KCl and BaCl2 salts), the flasks are provided with a droplet protection cover which comes from the condensation in order to avoid the hydration of the samples.The adsorption and desorption experiments were carried out at three different temperatures: 30, 40 and 50 °C and at six values of the relative humidity. The irradiated durum wheat was treated by gamma irradiation at a dose that is lower than 1 kGy, in the Regional Centre for Agricultural Research CRRA, Ionization Station Boukhalef, Tanger, Morocco.

The samples destined for the solid wheat desorption process are grains with nearly similar weights with a mass difference of 10-3g.Before being subjected to the adsorption process, the samples are dried in an oven set at a temperature of 100 °C for 24 hours.The experimental protocol in the study proceeds at the first time with the measurement of the sample masses. After that, they were placed into the jars. Then, the samples are weighed every two days until the mass variation between two successive measurements becomes about 1%. The thermodynamic equilibrium is then considered to be reached. As soon as the equilibrium-wet masses are determined, the samples are introduced into an oven at 105 °C. for 24 hours in order to determine their dry masses (Ms). Later, the moisture content X_{eq} at the hygroscopic equilibrium is based on the equation below [17]:

$$EMC = X_{eq} = \frac{M_h - M_s}{M_s} \quad (1)$$

Figure 1.A Temperature-controlled oven and watertight jars for the determination of sorption isotherms

Figure 1.B Jar containing the saturated salt solution and the product

2.2. Adsorption and desorption isotherms and its hysteresis phenomena

Moisture sorption isotherms are key tools that show the theoretical interpretation of the product's microstructure along with the physical interaction between solid and water. They also help to determine the thermodynamic data of the product under investigation. They are necessary for designing the pertinent calculations during the drying and storage processes as well as providing the equilibrium moisture content by the end of the process [8]. Finally, it is worth mentioning that the sorption isotherms enable us to calculate the optimal water activity, which gives room to the optimum of food conservation conditions. Another important tool adopted in this study is moisture sorption hysteresis. In fact, sorption hysteresis is of a paramount significance in providing theoretical and practical data of the food hygroscopic behavior. This tool also seeks to analyze the hysteresis effect of the product with respect to the monolayer moisture content [18]. Sorption hysteresis phenomenon takes place when two different paths are created between the adsorption and desorption isotherms. Accordingly, in desorption, the solid needs an amount of vapor pressure more than the case in adsorption.

2.3. Modelling of sorption isotherms

Given the complexity of the phenomena involved in the sorption of water, several factors must be taken into account to model the sorption curves:

- The nature and the hygroscopic state of the product;
- The nature of water molecules bonds;
- The solid matrix of the product and how equilibrium is reached.

In order to determine the relationship between the equilibrium moisture content and the water activity of durum wheat, we rely on several nonlinear regression models that represent the value of the moisture content in three zones: monolayer, multilayer and liquid water zones. It is significant to point out that a certain model might be suitable for a particular food and meanwhile proves to be unsuitable for another. Indeed, the model can only provide us with a predictive value of moisture content [19]. Another point to add is that certain regression models are not applicable over the entire range of relative humidity. In our study, we have adopted seven mathematical models so that we can find out the most convenient model that better describes the relationship between water activity and Equilibrium moisture content in adsorption and desorption phenomena at different temperatures, 30 °C, 40 °C and 50 °C. These models are presented with their corresponding equations as follows:

GAB [17] $$MC = \frac{M_0 CKa_w}{\left[(1-Ka_w)(1-Ka_w + CKa_w)\right]} \quad (2)$$

Peleg [20] $$MC = k_1 a_w^{n1} + k_2 a_w^{n2} \quad (3)$$

Modified Oswin [20] $$MC = (A - B\theta)\left[\frac{a_w}{1-a_w}\right]^C \quad (4)$$

Smith [20] $$MC = a - b\ln(1-a_w) \quad (5)$$

Oswin [20] $$MC = k\left(\frac{a_w}{1-a_w}\right)^n \quad (6)$$

Halsey [21] $$MC = \left(-\frac{A}{\ln(a_w)}\right)^{\frac{1}{B}} \quad (7)$$

Chung and Pfost [21, 22] $$MC = -\frac{1}{A}\left(\ln(-\frac{\theta \ln(a_w)}{B}\right) \quad (8)$$

It is worth noting that there is no specific model that can provide exact information of the moisture content data throughout the range of water activity. Hence, in order to choose the most convenient model, it is necessary to evaluate the coefficient of correlation (r) and the standard error of estimate (SEE) [17, 23].

$$r = \sqrt{\frac{\sum_{i=1}^{N}\left(Xeq_{i,pre} - \overline{Xeq}_{i,\exp}\right)^2}{\sum_{i=1}^{N}\left(Xeq_{i,\exp} - \overline{Xeq}_{i,\exp}\right)^2}} \quad (9)$$

$$ESS = \sqrt{\frac{\sum_{i=1}^{N}\left(Xeq_{i,\exp} - Xeq_{i,pre}\right)^2}{d_f}} \quad (10)$$

Where N is the number of data points; Xeqi,exp is the experimental moisture content (%d.b); Xeqi,pre is the predicted moisture content (%d.b).

2.4. Specific surface area of sorption

Calculating the specific surface area of sorption is very useful in determining the strong bonds that exists between water and solid. In this regard, the calculation of the specific surface area of sorption is conducted via the following equation [14]:

$$S = \frac{M_0 \times N_A \times A_m}{M_{wat}} = 35.3M_0 \quad (11)$$

Where S designates the solid surface area of sorption ($m^2.g^{-1}$ solids); M_0 refers to the monolayer moisture content (g/100 g, d.b); NA is the number of Avogadro (6.02 1023 molecules mol^{-1}); Am is the area of a water molecule (1.06 10-19 m^2/molecule). Finally, the M_{wat} represents the molecular weight of the water (18 $g.mol^{-1}$).

2.5 Net isosteric heat of sorption

The net isosteric heat indicates the required energy to fixe water to food product (Δhd). Calculating the isosteric heat of sorption (ΔHd) which represents the amount of energy for dehydration of food, necessitates the addition of the

value of the differential enthalpy to the heat of vaporization of the pure water (ΔHvap). This later can be calculated from the equation below [8]:

$$\Delta H_d = \Delta h_d + \Delta H_{vap} \quad (12)$$

Additionally, the Clausius–Clapeyron equation is used to determine the value of the net isosteric heat of sorption [9]:

$$\left[\frac{d(\ln a_w)}{d(1/T)}\right]_{X_{eq}} = \frac{-\Delta h_d}{R} \quad (13)$$

While using the sorption isotherms at different temperatures, we can determine the value of the water activity in accordance with a fixed equilibrium moisture content. Moreover, the logarithm of the water activity in function of inverse temperature is plotted. Another point to add is that a linear regression method is adapted to calculate the value of the net isosteric heat of sorption as it is shown in this equation:

$$\ln(a_w) = -\left(\frac{\Delta h_d}{R}\right)\frac{1}{T} + Cste \quad (14)$$

3. Results and discussion

3.1. Determination of the moisture sorption isotherm, the hysteresis and the optimum water activity

The Figure 2 and Figure 3 display the sorption isotherms of the irradiated and non-irradiated durum wheat in desorption and adsorption respectively. The table 2 summarizes the adsorption and desorption equilibrium moisture contents data of the samples at different water activities and temperatures. Additionally, these sorption isotherms represent the relation between the equilibrium moisture content (EMC) and the water activity (aw) at different temperature 30, 40, and 50 °C. In this regard, the prediction of the different storage conditions can be detected from the figures. Moreover, the EMC increases when the humidity increases or when the temperature decreases.

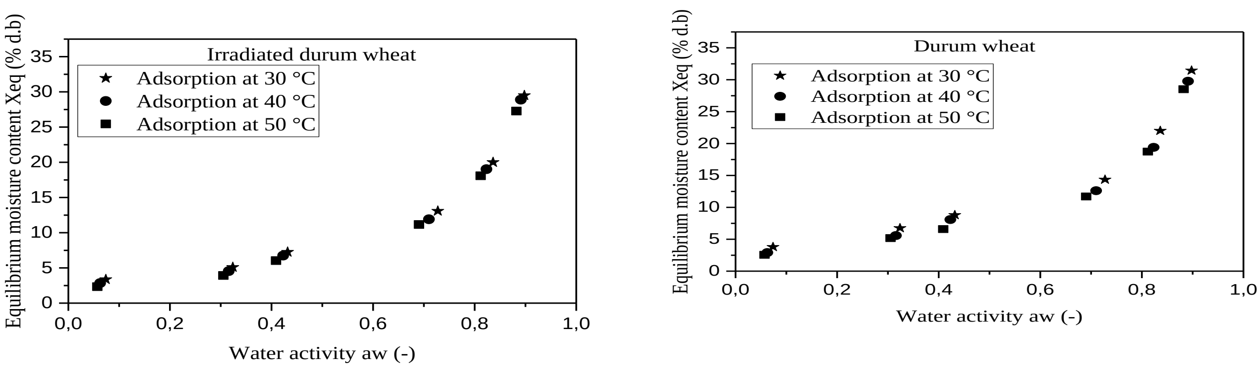


Figure 2. Moisture adsorption isotherms of the irradiated and non-irradiated durum wheat at 30 °C, 40 °C and 50

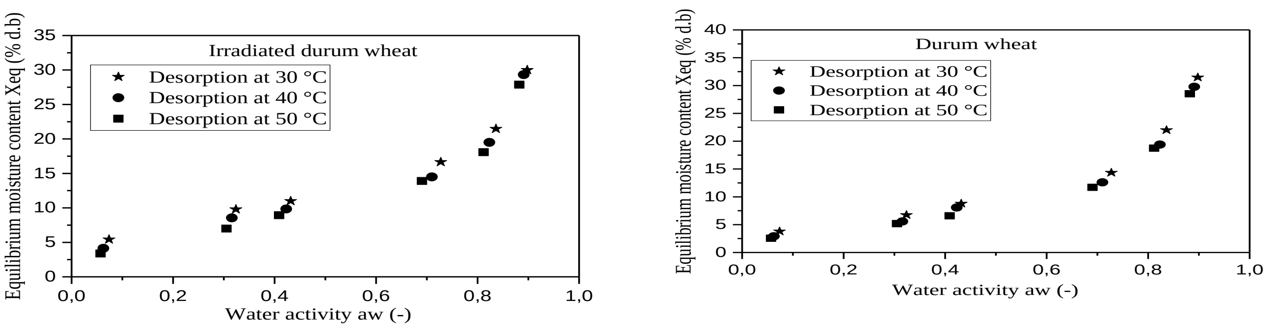


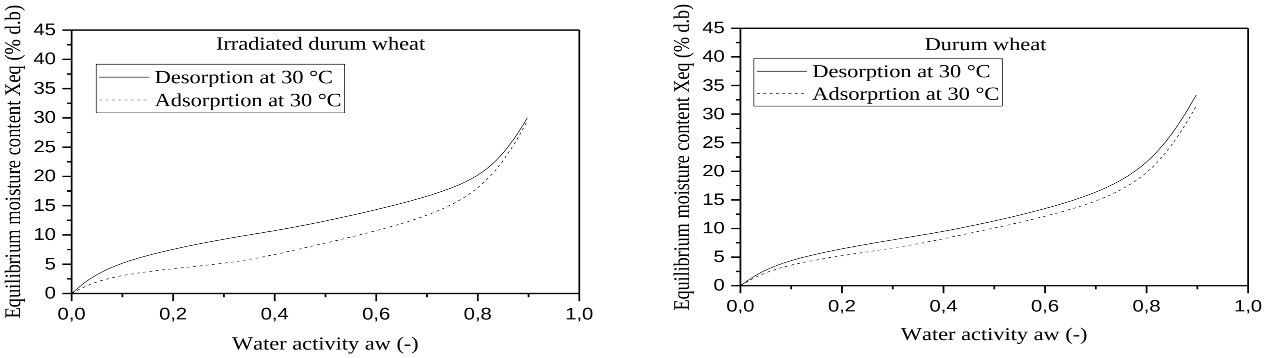
Figure 3. Moisture desorption isotherms of the irradiated and non-irradiated durum wheat at 30 °C, 40 °C and 50 ºC

Table 2. *Adsorption and desorption equilibrium moisture contents of the irradiated and non-irradiated durum wheat at different water activities and temperatures*

Samples	Temperature T(°C)	Water activities (aw)	Equilibrium moisture content (X_{eq}) (%d.b) ±0.001g	
			Adsorption	Desorption
Irradiated durum wheat	30	0.0738	3.371	5.43
		0.3238	5.1	9.791
		0.4317	7.25	10.989
		0.7275	13.085	16.661
		0.8362	20.012	21.476
		0.898	29.5	30.012
	40	0.0626	2.84857	4.129
		0.3159	4.53288	8.556
		0.423	6.74181	9.836
		0.71	11.905	14.487
		0.8232	19.0135	19.5
		0.891	28.8879	29.3178
	50	0.0572	2.34	3.375
		0.3054	3.924	6.996
		0.4091	6.039	8.933
		0.6904	11.165	13.9
		0.812	18.082	18.082
		0.8823	27.269	27.866
Non-irradiated durum wheat	30	0.0738	3.800	4.592
		0.3238	6.747	8.399
		0.4317	8.794	9.854
		0.7275	14.345	15.880
		0.8362	22.000	24.000
		0.8980	31.458	33.333
	40	0.0626	2.910	3.926
		0.3159	5.571	7.350
		0.4230	8.083	8.589
		0.7100	12.63	14.068
		0.8232	19.396	22.718
		0.8910	29.771	32.022
	50	0.0572	2.552	2.544
		0.3054	5.175	5.315
		0.4091	6.593	6.993
		0.6904	11.699	12.445
		0.8120	18.738	21.802
		0.8823	28.515	30.769

The findings from Figure 2 and Figure 3 are due to a higher temperature, which excites the water molecules state. Therefore, it weakens the force of the interaction between the solid and water [24]. Furthermore, we can note that the impact of the humidity on the stability of the irradiated and non-irradiated durum wheat in adsorption and desorption phenomena is higher than that of the temperature. Additionally, we can note from this figure that both samples isotherms have a sigmoid shape, according to the international union of pure and applied chemistry (IUPAC) classification these isotherms belong to the type II. Hence, the irradiated and non-irradiated durum wheat have a non-porous or macroporous adsorbent as well as they have an unrestricted monolayer-multilayer adsorption [26].

A



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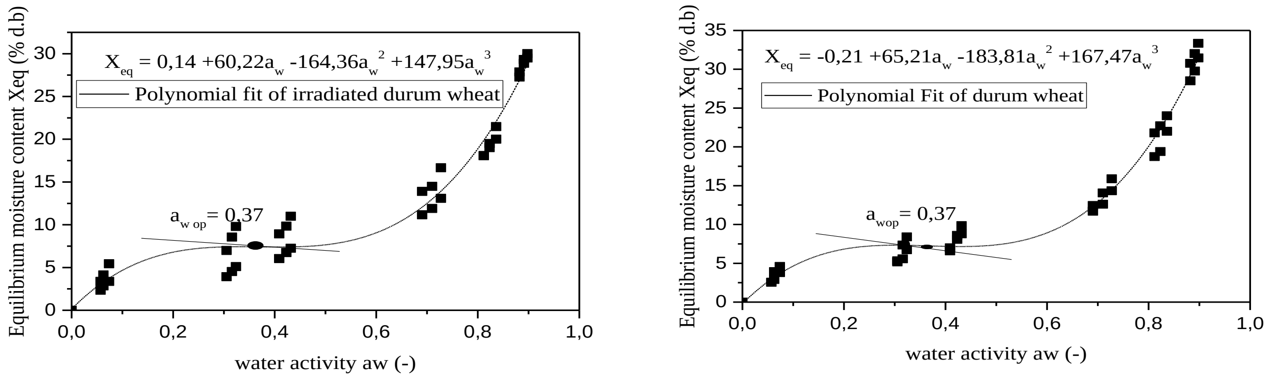

Figure 4. Moisture sorption data of the irradiated and non-irradiated durum wheat at 30 °C, 40 °C and 50 °C: (a) hysteresis; (b) the optimal water activity for conservation.

The Figure A.4 depicts the hysteresis phenomenon of both samples. In the case of adsorption, the curve fluctuates below the desorption curve at all the adapted temperatures. Another finding detected in this study is that they have an irreversible sorption phenomenon. In Figure A.4 the hysteresis cycle for the irradiated samples more curved than for the non-irradiated. This proves that the irradiated durum wheat is more hygroscopic than the other samples. The Figure B.4 shows the same optimal storage activity for both samples. The optimal water activity of irradiated durum wheat aw_{op} = 0.37 with EMC = 7.62 while the optimal water activity of non-irradiated durum wheat aw_{op} = 0.37 with EMC = 7.23. In addition, another point to add is that the conservation plateau of both samples ranges from 0.2 to 0.5. Therefore, the conservation of these products lasts for a long time. The difference in moisture sorption between the treated and untreated durum wheat can be explained by the fact that the gamma irradiation might probably interact with cell molecules which accordingly affects the physicochemical characteristics. Hence, the concentration of the water molecules in different levels of layers of the product affected by radiation at a lower [17]. Determining the optimal water activity of conservation of the product is an indispensable tool in all conservation applications. In fact, researchers provide us with this information so as to handle food while maintaining its good quality during the storage. Using the sorption isotherms modeling under a third-degree polynomial is helpful to determine the area of the product stability. This later refers to the optimal water activity (aw_{op}). According to literature, we can also note that the water activity of a large number of foods is ranged in 0.3–0.4 [7].

3.2 Modelling of sorption isotherms

Table 3. *Mathematical models used to describe desorption and adsorption isotherms of the irradiated and non-irradiated durum wheat.*

Irradiated durum wheat						
Models and parameters	Desorption			Adsorption		
	30 °C	40 °C	50 °C	30 °C	40 °C	50 °C
GAB						
M_0	6.37	5.33	4.49	3.93	3.72	3.67
K	0.87	0.91	0.93	0.96	0.98	0.98
C	88.31	73.03	43.71	52.83	37.22	19.78
R	0.99	0.99	0.99	0.99	0.99	0.99
SEE	1.53	1.65	1.40	0.48	0.49	0.51
Peleg						
K_1	43.66	59.94	16.46	10.15	47.91	44.87
K_2	10.59	12.21	0.64	0.47	7.66	6.98
N_1	16.69	15.64	75.73	45.51	9.47	8.96
N_2	0.45	0.50	14.29	7.81	0.48	0.53
R	0.99	0.99	0.99	0.99	0.99	0.99
SEE	0.73	0.45	0.86	0.93	0.86	0.84
Modified Oswin						
A	21.55	25.81	30.40	26.90	24.62	28.45
B	0.31	0.38	0.41	0.48	0.43	0.43
C	0.40	0.45	0.49	0.60	0.65	0.67
R	0.99	0.99	0.99	0.99	0.99	0.99
SEE	1.57	1.93	1.67	1.32	1.30	0.99
Smith						
A	4.81	3.44	2.58	0.83	0.31	0.05
B	10.18	10.54	10.73	11.41	11.66	11.16
R	0.99	0.98	0.98	0.98	0.98	0.98
SEE	1.58	2.05	1.85	2.15	2.29	2.03
Oswin						
K	12.09	10.64	9.80	7.81	7.25	6.69
N	0.40	0.45	0.49	0.60	0.65	0.67
R	0.99	0.99	0.99	0.99	0.99	0.99
SEE	1.36	1.67	1.44	1.14	1.13	0.86
Halsey						
K	90.05	38.81	25.01	11.79	8.85	7.42
N	1.99	1.74	1.61	1.39	1.29	1.23
R	0.99	0.99	0.99	0.99	0.99	0.99
SEE	0.90	1.19	1.07	0.46	0.49	0.37
Chung and Pfost						
A	0.14	0.14	0.14	0.13	0.13	0.13
B	131.62	150.03	169.95	76.96	124.78	121.26
R	0.97	0.96	0.96	0.95	0.94	0.94
SEE	2.34	2.88	2.75	3.50	3.73	3.52
Durum wheat						
Models and parameters	Desorption			Adsorption		
	30 °C	40 °C	50 °C	30 °C	40 °C	50 °C
GAB						
M_0	5.44	4.92	4.49	4.67	4.11 22	3.90
K	0.93	0.95	0.97	0.95	0.97	0.98
C	73.67	59.50	17.07	55.56	40.43	29.8
R	0.99	0.99	0.99	0.99	0.99	0.99
SEE	0.95	0.74	0.74	0.79	0.91	0.26
Peleg						
K_1	14.00	11.70	48.31	12.76	12.79	49.81
K_2	0.43	0.39	6.46	0.49	0.60	7.87
N_1	47.92	48.41	9.91	48.14	55.11	10.48
N_2	8.15	7.28	0.48	8.50	9.8	0.53
R	0.99	0.99	0.99	0.99	0.99	0.99
SEE	0.17	0.20	0.44	0.55	0.78	0.50
Modified Oswin						
A	21.55	-14.59	-20.35	-9.82	-15.40	-20.69
B	0.31	0.61	0.57	0.64	0.59	0.57

C	0.39	0.55	0.65	0.54	0.60	0.64
R	0.99	0.99	0.99	0.99	0.99	0.99
SEE	1.57	1.69	1.19	1.50	1.60	1.25
Smith						
A	2.81	1.89	0.20	1.79	1.02	0.47
B	12.33	12.51	13.26	11.89	11.68	11.87
R	0.98	0.98	0.98	0.98	0.98	0.98
SEE	2.06	2.21	2.16	2.11	2.33	2.17
Oswin						
K	10.90	9.82	8.30	9.36	8.21	7.63
N	0.5	0.55	0.65	0.54	0.60	0.64
R	0.99	0.99	0.99	0.99	0.99	0.99
SEE	1.44	1.47	1.03	1.30	1.39	1.08
Halsey						
K	31.62	19.65	10.12	19.34	12.24	9.20
N	1.63	1.48	1.28	1.51	1.38	1.29
R	0.99	0.99	0.99	0.99	0.99	0.99
SEE	0.69	0.74	0.67	0.62	0.83	0.40
Chung and Pfost						
A	0.11	0.12	0.11	0.12	0.12	0.13
B	94.81	118.41	124.25	85.29	107.85	129.03
R	0.96	0.95	0.95	0.96	0.95	0.94
SEE	3.34	3.66	3.81	3.39	3.57	3.58

Table 3 and Table 4 illustrate the values of the coefficients of the seven models used in the study as well as their statistical parameters: the coefficient of correlation (r) and the standard error of estimate (SEE) respectively. These results are calculated by using curvxpt 1.3 software with a nonlinear regression fitting technique. After analyzing the statistical parameters in table 3 and table 4, the Halsey model is selected as a suitable model that will represent the adsorption and desorption isotherms of the irradiated durum wheat. While the suitable model that will represent the sorption isotherms of the non-irradiated durum wheat is the GAB model. The GAB model is based on physical bases. Therefore, the Guggenheim, Anderson, and de Boer model helps in the analysis of the physicochemical surface phenomena with reference to a localized and homogeneous multi-molecular adsorption theory [26].

Table 4. *Parameter standard error of estimate (SEE) of the seven equations fitted to the adsorption isotherms of of the irradiated and non-irradiated durum wheat.*

Models	Irradiated durum wheat						Durum wheat					
	standard error of estimate (SEE)						standard error of estimate (SEE)					
	30 °C		40 °C		50 °C		30 °C		40 °C		50 °C	
	Ad	Des	Ad	Des	Ad	Des	Ad	Des	Ad	Des	Ad	Des
GAB	0.48	1.53	0.49	1.65	0.51	1.40	0.79	0.95	0.91	0.74	0.26	0.74
Peleg	0.93	0.73	0.86	0.45	0.84	0.86	0.93	0.73	0.86	0.45	0.84	0.86
Modified Oswin	1.32	1.57	1.30	1.93	0.99	1.67	1.32	1.57	1.30	1.93	0.99	1.67
Smith	2.15	1.58	2.29	2.05	2.03	1.85	2.15	1.58	2.29	2.05	2.03	1.85
Oswin	1.14	1.36	1.13	1.67	0.86	1.44	1.14	1.36	1.13	1.67	0.86	1.44
Halsey	0.46	0.90	0.49	1.19	0.37	1.07	0.46	0.90	0.49	1.19	0.37	1.07
Chung and Pfost	3.50	2.34	3.73	2.88	3.52	2.75	3.50	2.34	3.73	2.88	3.52	2.75

Des: Desorption; Ad: Adsorption

The values of M_0 (a coefficient of The GAB model) in desorption at three temperature 30 °C, 40 °C and 50 °C, are 6.37, 5.33 and 4.49 g/100 (d.b) respectively. These values correspond the irradiated durum wheat. Concerning the non-irradiated durum wheat, M0 takes the values of 5.44, 4.92 and 4.49 g/100 (d.b) at 30 °C, 40 °C and 50 °C temperatures respectively. On the other hand, the values of M0 in the adsorption of the two samples, irradiated and non-irradiated durum wheat, at 30 °C, 40 °C and 50 °C, are 3.93, 3.72, and 3.67 g/100 (d.b); 4.67, 4.11 and 3.90 g/100 (d.b) respectively. From these findings, we deduce that the monolayer moisture content increases along with the decrease of the temperature. Additionally, the M_0 value in desorption is higher than that in adsorption at a fixed temperature. This phenomenon is attributed to the fact that as long as the temperature gets a higher degree, the water molecules get the amount of energy necessary to loosen from their sorption sites. Therefore, the monolayer moisture content (M_0) value decreases.

3.3 Specific surface area of sorption

Using the Eq. (11) the values of the specific surface area of adsorption and desorption were calculated. The M_0, which refers to the GAB monolayer moisture, is obtained from the GAB model. On one hand, the adsorption surface area at 30 °C, 40 °C and 50 °C temperatures, the irradiated durum wheat takes the values of 224,861 $m^2.g^{-1}$; 188,149 $m^2.g^{-1}$; 158,497 $m^2.g^{-1}$ respectively; and concerning the variety durum wheat, it takes the values of 164.851 $m^2.g^{-1}$; 145.083 $m^2.g^{-1}$; 137.67 $m^2.g^{-1}$ respectively. On the other hand, the values of desorption surface area of the irradiated durum wheat takes the values of 138,729 $m^2.g^{-1}$; 131,316 $m^2.g^{-1}$; 129,551 $m^2.g^{-1}$ respectively; and concerning the non-irradiated durum wheat, it takes the values of 192.032 $m^2.g^{-1}$; 173.676 $m^2.g^{-1}$; 158.497 $m^2.g^{-1}$ respectively. Hence, we can conclude that the temperature affects the interaction between the water and solid surface area. In addition, it decreases the adsorption surface area in a way that is larger than that in desorption. In the literature, the value of the specific surface area of food sorption is ranged between 100 $m^2.g^{-1}$ and 250 $m^2.g^{-1}$ [27].

3.4 Net isosteric heat of sorption

The net isosteric heat of adsorption and desorption of the irradiated and non-irradiated durum wheat has been calculated from the sorption isotherm data and the Clausius–Clapeyron equation Eq. (13). The Figure 5 shows the different values of the differential enthalpy of sorption concerning the both samples. This energy takes the highest value at the lowest value of the equilibrium moisture content.

Furthermore, we can note from the expressions below that the durum wheat heat variety untreated durum wheat is higher than treated durum wheat in adsorption; whereas, we find the opposite of this inequality in the desorption phenomenon. We can also observe that the energy of both of the irradiated and non-irradiated, in adsorption is lower than in desorption.

Irradiated durum wheat desorption:	$253.13 - 57.83X_{eq} + 4.63X_{eq}^2 - 0.13X_{eq}^3$	r = 0.99
Durum wheat desorption:	$170 - 38.92X_{eq} + 3.01\,X_{eq}^2 - 0.08\,X_{eq}^3$	r = 0.99
Irradiated durum wheat adsorption:	$32.70 - 7.13X_{eq} + 0.55\,X_{eq}^2 - 0.01\,X_{eq}^3$	r = 0.99
Durum wheat adsorption:	$75.32 - 16.47X_{eq} + 1.25\,X_{eq}^2 - 0.03\,X_{eq}^3$	r = 0.99

The Figure 5 illustrates the existence of a stronger bond between the water molecules and the surface of the substrate than that of other layers. In this respect, the isosteric net heat of sorption decreases when the water content increases. It is actually due to a lessening of interference between water molecules and the solid at the surface of the product [7].

The isosteric heat of sorption is used to determine the nature of the bonds of water within the product. The low values indicate physisorption; physical adsorption; (ΔHd < 100 kJ/mol), while the high values indicate sorption chemistry [28].

4. Conclusion

Implementing a comparative study of the hygroscopic behavior of the irradiated and non-irradiated durum wheat, as well as their thermodynamic properties, is key tools that help analyze the impact of gamma irradiation on durum wheat (*Triticum durum L.*) in moisture sorption. The experimental results display that the sorption isotherms of both samples are of sigmoid shape. This means that the treated and untreated durum wheat are characterized by being nonporous or microporous solids. Additionally, the impact of the humidity on food stability is higher than that of the temperature. Another significant point to mention is that both of the samples have the same value of the optimal water activity needed for their conservation which correlates with aw_{op} = 0.37. In our attempt to opt for a convenient model that better describe the relationship between water activity and equilibrium moisture content, we rely on seven models. The Halsey model is selected as a suitable model of sorption isotherms of irradiated durum wheat. While the suitable model of the sorption isotherms of the non-irradiated durum wheat is the GAB model. In addition, the thermodynamic properties of the irradiated and non-irradiated durum wheat investigated namely net isosteric heat of sorption (Δhd) and specific surface area of sorption (S) prove to have a different hygroscopic behavior. Concisely, the outcomes show that the gamma irradiation at a lower dose affect the moisture sorption of the durum wheat

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