

Modeling and the role of water activity, desorption isotherm and glass transition in drying of potatoes quality and shelf life stability

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ABSTRACT

In drying, evaluation of desorption isotherm of the sample is important to determine the optimum residual moisture contents of dried products at its stable water activity. Determination of glass *transition temperature of the sample helps to decide to process the samples in its glass state for better quality product production. In this paper, the concept of water activity, desorption isotherms and glass transition temperatures* related to product safety, stability and quality were reviewed. The desorption isotherm and glass transition temperatures of potato were also determined, and the experimental data were fitted to the existing models. The GAB model shows the best fit between experimental and predicted values of desorption isotherm data. Stable water activity and optimum residual moisture content of potato slices when the samples dried at different temperatures and a hint for drying the samples for better retention in product quality were presented in the result.

Key words: water activity, desorption isotherm, glass transition temperature and modeling

1. Introduction

Water is the most abundant element in food. According to most food-scientist, water has two broad forms that is bound and unbound. Unbound water has many roles in food processing and a great impact on food reaction and food quality[1]. The water activity (a_w) of a foodstuff is defined as the current volume and the availability of free water in the food, which is available for the growth of microorganisms as well as enzyme and chemical reaction. The relationship between a_w and moisture content at a given temperature is called the moisture sorption isotherm. Glass transition temperature (T_g) represents the pattern of change in the state of a material as a function of decreasing the levels of moisture content[2]. Water activity, moisture sorption isotherm and glass transition temperature (T_g) are essential properties in drying. The concept of water activity has been used as a reliable assessment of the microbial growth, lipid oxidation, non-enzymatic and enzymatic activities[3]. It helps to decide a_w of the drying sample at which the sample is stable. Once a_w of the samples at which the sample could be stable is known. From moisture sorption isotherm data it is possible to predict the corresponding optimum residual moisture content of the drying sample to decide the end-point of drying process[4]. Whereas the glass transition

temperature can be taken as a reference parameter to characteristic properties of safety, stability, and quality[5].

As discussed in the previous paragraph a_w used to describe the stability of the product. However, a_w concept does not indicate exactly when the molecular mobility starts[3]. The T_g concept can fill the gap of the molecular mobility starting point. That means the a_w concept is based on the binding nature of water molecules in the matrix. When water is bound (i.e., unavailable to take part in reactions) to the solid matrix or non-solvent, then no deterioration reactions could be expected. The T_g concept is based on the molecular mobility of the reacting components in the matrix. When diffusion of the reactants through the system to take part in reactions is very slow then stability is achieved. On another hand, According to many authors drying processes stopped when the graph of mass of the samples versus time became almost constant. This method does not have a clear ending point of the drying process. One process may end with a long constant line whereas the other one may stop at a short constant line. The former may result in loss of time, quality and energy when the samples dried over required a_w and the latter may result in less stable product when the samples dried under required a_w . To stop the drying process at optimum

residual moisture content (equivalent to at stable a_w) of the sample a determination of desorption isotherm was required. To develop a stable product with better quality, the combined knowledge of water activity, desorption isotherm and glass transition temperature is required. In this study, the relationship between water activity, sorption isotherm properties, and glass transition temperature were reviewed, the desorption isotherm and glass transition temperature of potatoes were determined, and the desorption isotherm and glass transition temperature of potatoes' experimental data were fitted to existing models.

NOMENCLATURE

a_w	water activity
A, B and C	dimensionless constants in the sorption isotherms models
T_g	glass transition temperature of the binary mixture
M	equilibrium moisture content kg/kg
M_i	experimental values (Eq. (4))
M_o	monolayer moisture content (kg/kg, dry basis)
M_{Pi}	predicted values (Eq.(4))
K	dimensionless constant in the sorption isotherms models
R	universal gas constant (J/mol K)
T	absolute temperature (K)
T_{gw}	glass transition temperature of the water
T_{gs}	glass transition temperature of the dry matter
W_s	weight fraction of dry matter
W_w	weight fraction of water
Subscripts	
i	i^{th} experimental observation
N	number of experimental observation

chemical reactions are presented as a function of water activity. From a_w map it is clearly observed that, above a_w greater than 0.7, stability can be decreased with increasing water activity due to mold fungi, yeasts and bacteria growth. In a range of a_w between 0.2 and 0.7 stability can be decreased with increase in a_w due to lipid oxidation, non-enzymatic browning and enzymatic reactions. In a range below a_w less than 0.2, stability can be decreased with decrease in a_w due to lipid oxidation. With a_w at 0.2, the product is most stable with respect to lipid oxidation, non-enzymatic browning, enzyme activity, and of course, the various microbial parameters. Rahman, [7] also reported most stability of a dried product at its monolayer moisture content and its instability above or below monolayer. Therefore, to get most stable dried products, it is preferred to dry samples until its water activities reached to its monolayer moisture content. To stop drying process at its monolayer moisture content, it is necessary to know the water activity and moisture content relationship in the drying samples. At a given temperature, the relationship between a_w and corresponding moisture content is characterized by the moisture sorption isotherm[3]. An increase in a_w is always accompanied by an increase in the water content in a nonlinear fashion. It is necessary to fit the experimental data in to an appropriate model in order to predict or calculate the equilibrium moisture content of the drying sample at specific a_w .

2. Literature review

2.1. The role of water activity and Sorption isotherm in drying process

It is obvious by reducing the amount of water in food it is possible to extend the shelf life of food. Drying is one of the most popular methods used for food preservation. The basic objective of drying food products is the reduction of moisture in the product up to a certain level, at which microbial spoilage and deterioration chemical reactions are greatly retarded[6]. The chemical, physical and microbiological stability of drying sample highly depends on the water content and its interaction with food ingredients[3]. a_w has a fundamental role in the drying process and food stability. Stability diagram map based on the a_w presented in Fig.1. In this present map, the trends of microbial growth and bio-

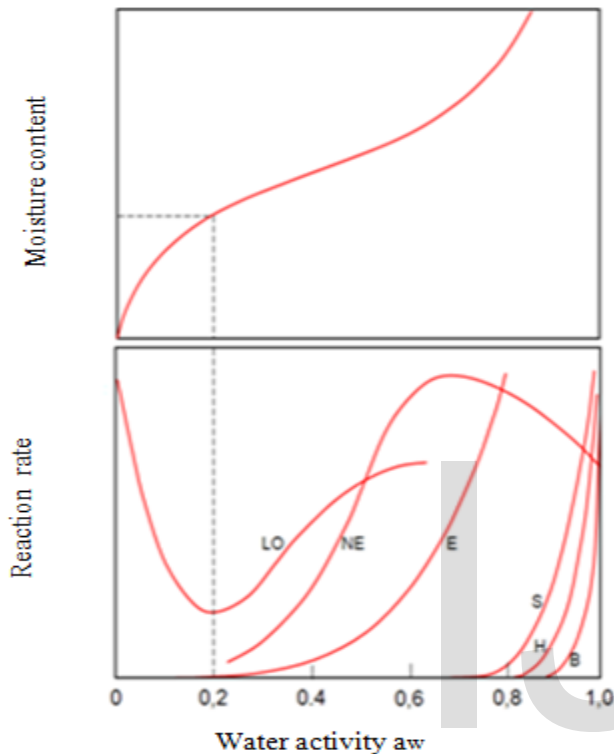


Fig .1. Stability diagram. LO lipid oxidation, NE non-enzymatic browning, E enzymatic reactions, S, H, B spoilage by mold fungi, yeasts, bacteria [Sturm et al., 2010][8] (The language is translated from German to English version)

2.1.1. Moisture sorption models

A number of models (Appendix Table. 1) used to fit desorption isotherm data of potatoes by different authors at different temperatures. All authors listed in this appendix table reported the suitability of GAB model (equation 1) for representing the relationship between the a_w and the equilibrium moisture content of potatoes. However, the equilibrium moisture content values obtained at a specific water activity by different authors for the same product (potatoes) using the same model (GAB) are not similar, since the constant values are not the same for the same product at the same temperature as shown in Table 1. For example, comparing constant value results of desorption isotherm of potatoes at

temperature of 60 °C obtained by McLaughlin and Magee, [9] were 109.7, 1.138 and 4.27 times the value obtained by McMinn and Magee,[10] for X_m , K, and C respectively. The result of the K value obtained by Chemkhi et al. [11] for desorption isotherm of potatoes was increased from 0.976 to 0.993 when the temperature increased from 50 to 70 °C. In contrary, the value of K obtained by Wang and Brennan,[12] was decreased from 0.82 to 0.80 when the temperature increased from 50 to 70 °C. Therefore, Determination of desorption isotherm of potatoes was preferred to get the accurate value residual moisture content for drying a specific variety.

$$M = \frac{M_oCKa_w}{(1 - ka_w)(1 - Ka_w + CKa_w)} \text{-----(1)}$$

Where C and K are constants in the sorption isotherms models, a_w is the water activity, M_o is the monolayer moisture content (kg/kg,dry basis), M equilibrium moisture content kg/kg, dry base, T is the absolute temperature(K)

Table. 1. Constant values of GAB model of desorption isotherm of potatoes at temperature of 50, 60 and 70 °C

X_m	K	C	E%	T (°C)	M (kg/kg,dry base) at $a_w=0.2$	Authors
0.209	0.976	4.416	0.538	50	0.26	[11]
0.061	0.82	8.89	6.74	50	0.13	[12]
0.053	0.84	8.57	4.59	60	0.11	[12]
4.620	0.84	19.99	3.13	60	11.59	[9]
0.042	0.738	4.68	5.58	60	0.04	[10]
0.086	0.993	3.316	0.143	70	0.09	[11]
0.057	0.800	4.37	9.15	70	0.06	[12]

2.2. Glass transition temperature

Glass transition temperature (T_g) indicates the molecular mobility starting point of the solid matrix. In the glassy state, molecular mobility is extremely slow, due to the high viscosity of the matrix. The increase in temperature of a product above its T_g increases molecular mobility and also affects diffusion of the matrix and results in an increase in rates of deterioration: enzymatic reaction, non enzymatic browning and oxidation[13]. Thus, the T_g value can be taken as a reference parameter to characterize properties like quality, stability and safety of food systems[6]. Foods can be considered as stable at the glassy state, since in the state compounds involved in the deterioration reactions take times to diffuse

over molecular distances and approach each other to react[14]. Sablani, [4] pointed out that certain physicochemical and structural processes such as stickiness, crispness, collapse, amorphous-to-crystalline transformations and the rates of non-enzymatic browning are better correlated to the glass transition temperature through plasticization by water or temperature than water activity. Differential scanning calorimeter (DSC) is by far the most commonly used method for determination of T_g in almost all cases, However, DSC said to be not sensitive enough to detect glass transition in materials such as starch containing products[15].

3. Materials and methods

3.1. Preparation of samples

Potato of Belena variety was purchased from a farmer (Lake Constance region, Germany) and it was stored at a temperature of 4°C. To start the experiment, good potatoes were selected, washed, and then sliced (Model Graff, Germany) into 2 and 3.5 mm thickness for desorption isotherm and glass transition temperature analysis respectively.

3.2. Determination of desorption isotherms

The standard static gravimetric method indicated in European Cooperative Project COST 90, Wolf et al.[17] was used to determine desorption isotherms of potatoes. Eight saturated salt solutions were selected to get different relative humidity. The salt solutions were prepared according to COST-90 Project (Table 2). The relationship between water activity (a_w) and temperature of saturated salt solutions was calculated using equation 2 as reported in Labuza *et.al.*, [16] for high temperatures. In order to prevent fungal activity a small quantity of thymol was placed in a glass jar[17]. Triplicate samples of 3 g ± 0.001 g were used to determine desorption isotherms at temperatures of 60, 70 and 80 °C. The samples were weighed in an interval of 24 h, and were allowed to equilibrate until there was no significant weight change, as evidenced by the difference between two consecutive measurements of weight values equals' ±0.001 g.

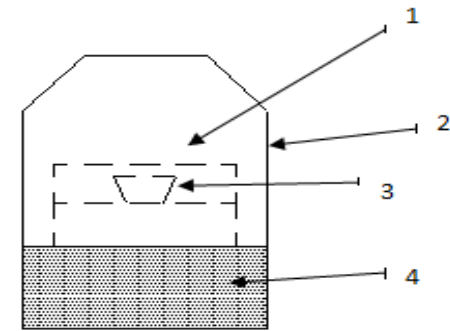


Fig. 2. Schematic diagram of the equipment for determination of equilibrium moisture content (1= Samples, 2= glass Jar , 3= thymol 4=.Salt solution)

Table. 2. Quantities of salt and distilled water used in the preparation of saturated salt solutions (Wolf et al.,[17] according to COST-90 Project

	Salt (g)	H ₂ O (g)	60 °C a _w	70 °C a _w	80 °C a _w
LiCl	75	42	0.096	0.092	0.088
CH ₃ COOK	200	75	0.175	0.162	0.151
K ₂ CO ₃	200	90	0.421	0.416	0.411
Mg(NO ₃) ₂	150	23	0.473	0.458	0.454
NaBr	200	80	0.490	0.471	0.454
NaCl	200	60	0.703	0.689	0.676
(NH ₄) ₂ SO ₄	200	60	0.788	0.783	0.778
KCl	200	80	0.751	0.727	0.705

$$\ln(a_w) = \frac{K_1}{T} - K_2 \dots \dots \dots (2)$$

Where: K₁ and K₂ are constants, different for each salt; T is the temperature in Kelvin. Table 3 gives the values for a range of salts based on experimental data reported in Labuza *et.al.*[16]

Table.3. Constant values of different salts (Labuza *et al.*, [16])

Salt	K ₁	K ₂
Lithium chloride (LiCl)	500.95	3.85
Magnesium nitrate (MgNO ₃)	356.6	1.82
Potassium acetate (KC ₂ H ₃ O ₂)	861.39	4.33
Potassium carbonate (K ₂ CO ₃)	145.00	1.3
Potassium chloride (KCl)	367.58	1.39
Sodium chloride (NaCl)	228.92	1.04
Sodium bromide (NaBr)	447.81	2.06
Ammonium sulfate (NH ₄) ₂ SO ₄	76.8191	0.469

3.3. Procedure to determine glass transition temperature by texture analyzer

Glass transition temperature was determined according to Addisalem and Hofacker [18]. Rahman, [19] also defined glass transition as time-temperature dependent transition, which is characterized by a discontinuity or change in slope of mechanical and other properties of a material, when plotted as a function of temperature. The mass of the fresh samples as well as the mass of each sample was measured immediately during withdrawal of drying process. Out of twenty-eight potato slices, four slices were randomly selected and used for mechanical properties analysis of fresh samples. The remaining slices were randomly placed in a convective oven. Four slices were withdrawn from the oven at a regular time interval during drying process for the analysis. The samples were analyzed by compression test using a texture analyzer (CT3-1500, USA). The sample was placed on the hollow planar base. The force was then applied to the sample by a 3 mm cylindrical probe. The downward movement of the cross head of the texture analyzer was adjusted at 2.00 mm/s until it bent the sample, pre-test speed, and post test speed were the same as test speed of the probe[20]. Hardness and work data were recorded. The analysis was continued at least until one value higher than minimum in hardness and work value was observed. From the graph of hardness /work versus moisture ratio of samples dried by constant temperature, the moisture ratio at which minimum value of work and hardness was observed, used as transition point from rubbery state to glassy. Finally, the graph of the glass transition temperature versus the moisture ratio was plotted.

3.4. Comparison of desorption Isotherm models

Table. 4. Models fitted to determine desorption Isotherms of Potatoes

Name of models	Models
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GAB [20]	EMC= CKX _m a _w /[(1 - Ka _w) (1 - Ka _w + CKa _w)]
Oswin [21]	EMC= A(a _w /(1 - a _w)) ^B
Halsey [22]	a _w = exp(-A/EMC ^B)
BET [23]	EMC= CX _m a _w /[(1 - a _w)+(C-1)(1-a _w) a _w]

A, B, C and K =constants in sorption isotherm models; a_w=water activity; EMC = equilibrium moisture content (dry basis); X_m = monolayer moisture content (dry basis)

3.5. Evaluation of models

To evaluate the goodness of fit of each equation, the mean relative percentage deviation modulus (E) was used Aguerre *et al.*,[25] and defined as indicated in Eq. 3:

$$E(\%) = \frac{100}{N} \sum_{i=1}^N \frac{M_i - MP_i}{M_i} \quad \text{---(3)}$$

Where M_i and M_{Pi} are experimental and predicted values, respectively, and N is the number of experimental data.

3.5. Data analysis

The glass transition temperature's data was fitted to Gordon–Taylor model (Gordon and Taylor, [26]): Minitab 16 software was used for plotting graph and all data analysis.

$$T_g = \frac{W_s T_{gs} + KW_w T_{gw}}{W_s + KW_w} \quad \text{---(4)}$$

The glass transition temperature of the water (T_{gw}) is -135°C [26]. T_g and T_{gs} are glass transition temperature of the binary mixture and the dry matter (solids), respectively. W_s and W_w indicate weight fraction of dry matter (solids) and water respectively. The parameter k is a constant of the model

4. RESULTS AND DISCUSSION

4.1. Equilibrium moisture content and a_w

The equilibrium moisture content of potatoes versus a_w at different temperature levels (60, 70, and 80 °C) are presented in Fig.3. From this graph, an increase in equilibrium moisture content with increasing water activity at constant temperature can clearly be seen. This change in the equilibrium moisture content is due to difference in vapor pressure gradient between the samples and the water activities of the solution (atmospheric humidity). At a constant water activity, equilibrium moisture contents

increase with decreasing temperature. McLaughlin and Magee, [9] reports an increase in temperature will decrease the binding energy between molecules due to an increase in state of excitation, the molecule's mutual distances increase and the attractive forces decrease. Quirijns et al. [28] also reports an increase in temperature induces a reduction in the equilibrium moisture content at a specific water activity since the molecules become less stable and break away from the water binding site of the food materials.

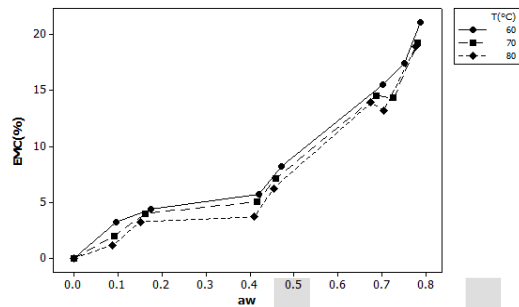


Fig.3 Desorption isotherms of potatoes at different temperatures.

4.2. Fitting of models to isotherm graphs

The parameters (Table 5) were estimated by fitting the mathematical model to the experimental data, using the method of direct nonlinear regression. The mean relative deviation modulus (E) and the estimated constants for the models in Table 4 are presented in Table 5. A model is considered to be suitable if its E value is less than 10% [10].

Table.5. Parameter Values for all Models in Desorption

Models	Parameters	Temperature (°C)		
		60	70	80
GAB	Xm	6.569	6.564	6.136
	C	5.517	4.311	4.158
	K	0.860	0.840	0.820
	E%	3.022	1.052	0.887
Oswin	A	8.997	7.990	7.279
	B	0.626	0.668	0.758
	E%	3.495	2.787	3.803
Halsey	A	0.019	4.14E+027	2.688
	B	0.006	1.55E+027	1.152

BET	E%	48.92	48.43	50.57
	Xm	0.290	0.346	0.521
	C	16.941	13.699	9.674
	E%	4.987	4.048	4.017

As indicated in Table 5, except Halsey, all other models showed a smaller mean relative percentage deviation ($E < 10\%$); therefore, they were suitable for fitting experimental data. However, among all models, the smallest mean relative percentage deviation was obtained for the GAB model. This shows that the GAB model gave the best fit for desorption isotherm of potatoes. This is in agreement with results reported in Wang and Brennan, [12] and Kaymak-ertekin and Gedik, [29]. Fig. 4, Fig. 5, and Fig. 6 depict comparisons of data between experimental and predicted values of desorption isotherm at 70 °C for GAB, BET, and Oswin models respectively. The figures show a reasonable agreement between experimental and predicted values. However, a model according to Halsey (Halsey, [23]) showed a poor fit over the entire range of equilibrium moisture contents. As shown in figure 7, the theoretically predicted, isotherm, lies below the experimentally determined isotherm and large mean relative percentage deviations (greater than 10%) were obtained. The result also agrees with the result of Wang & Brennan, [12].

As shown in Table 5, the monolayer moisture content values of constant K and C of the GAB model decrease as the temperatures increase. The decrease in monolayer moisture contents is might be due to structural modification in starch polymers with an increase in temperature [9]. An increase in temperature results in the reduction in the degree of hydrogen bonding in the polymers, thereby decreasing the availability of active sites for water binding and, thus, the monolayer moisture content [9]. To determine the residual moisture content of the sample during drying, GAB model was used since this model is fitted best for the experimental data. The corresponding equilibrium moisture content of the samples was calculated by substituting the water activity in GAB model by taking constant values from table 5. The result shows that the equilibrium moisture content of the sample at water activity of 0.2 were 4.2, 3.6 and 3.3% (dry bases) for samples drying at temperatures of 60, 70 and 80°C respectively. This shows that the samples of potato slices have to be dried until the moisture ratio of the samples reached 0.042, 0.036 and 0.033 in dry base for temperatures of 60, 70 and 80 °C respectively.

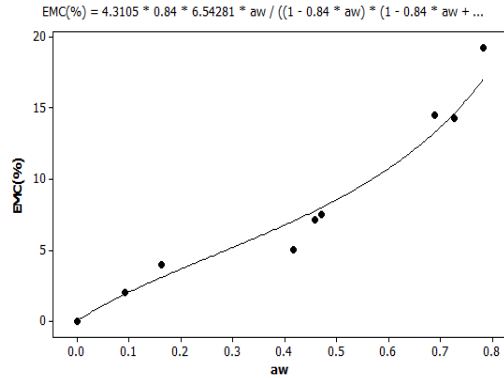


Fig.4. Comparison between experimental and predicted values of the desorption isotherm using the GAB equation at a temperature of 70°C.

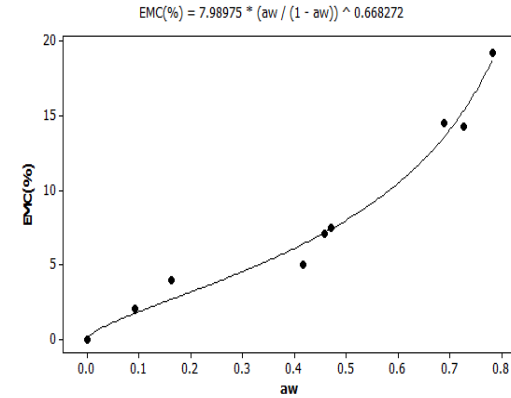


Fig.6. Comparison between experimental and predicted values of the desorption isotherm using the Oswin equation at a temperature of 70°C.

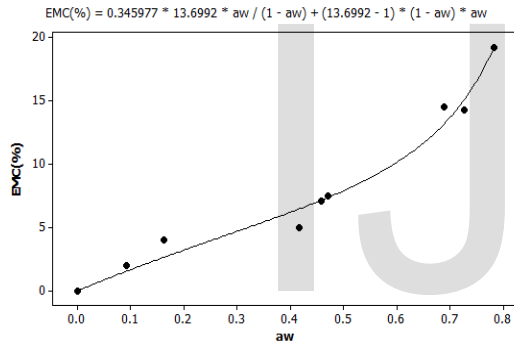


Fig.5. Comparison between experimental and predicted values of the desorption isotherm using the BET equation at a temperature of 70 °C

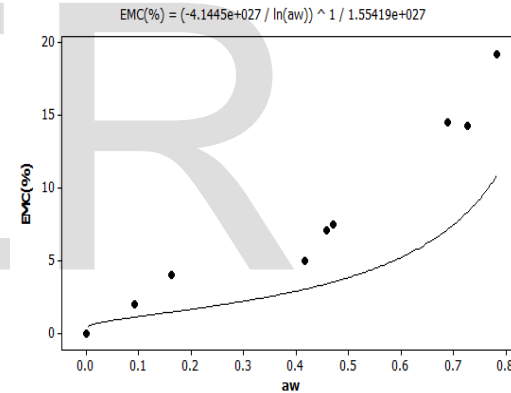


Fig. 7. Comparison between experimental and predicted values of the desorption isotherm using the Halsey equation at a temperature of 70°C

4.3. Glass transition temperature

As mentioned in the literature DSC is not suitable for determination of Tg of real food. Tg is defined, the temperature at which an amorphous system changes from the glassy (hard) to the rubbery state (soft). In this paper, the soft point used as indicator of Tg in terms of hardness and work by analyzing the sample using texture analyzer [18]. When the sample become soft, it is clear that, the force and the energy (work) required for bending the sample becomes smaller. The graph of hardness and work versus moisture ratio of hot air dried potato slices at a temperature of 70 °C are presented in Fig.8 and 9 respectively. Up to 0.25, as moisture ratio of the samples decrease, a decrease in hardness (the resistance of the samples for bending) and the

work required to overcome the internal strength, were observed. At a moisture ratio of 0.25, the samples attained its minimum hardness value (soft) and work. A temperature of 70 °C was taken as glass transition temperature at a moisture ratio of 0.25 for the samples dried at a temperature of 70 °C. In a similar way, the glass transition point for other temperatures was determined. Concerning mechanical properties of potatoes, the trends of the result agree with the report of Moyano et al.,[30]. Moyano and others reported that during thermal processing, the raw potato tissue becomes progressively softer and then it turns harder later.

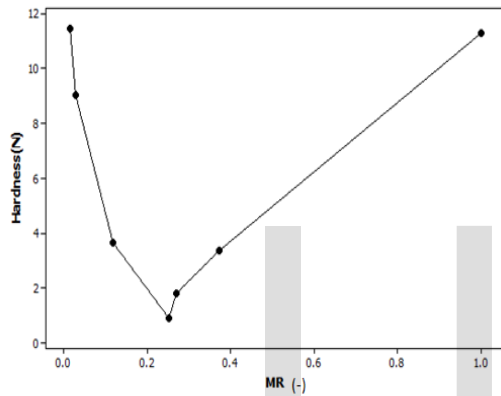


Fig.8. Hardness versus moisture ratio of samples dried at temperature 70°C

Fig. 10 shows a glass to rubber transition diagram of potato, the line representing the glass temperature at different moisture ratio. The glass transition point is the transition temperature at given moisture ratio where a transition from a glassy stable (solid state) to a rubbery (soft) state can begin to take place. For each moisture ratio, there was a unique glass transition temperature. Figure 10 depicts that, as moisture content decrease a trend of increase in glass transition temperature was observed. For example, the glass transition point of potato slice at MR of 0.26 was 70°C (Fig.10). This means the molecular mobility of the matrix for the samples dried at a temperature of 70 °C start at MR of 0.26. However, the optimum residual moisture content of the samples at its table a_w ($a_w= 0.2$) for the sample dried at 70 °C is 0.036 as discussed under sub title fitting of models to

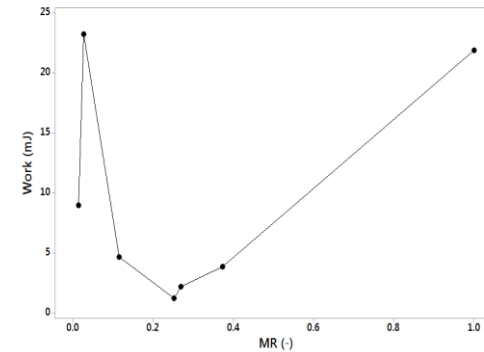


Fig.9. Work versus moisture ratio of samples dried at temperature of 70°C

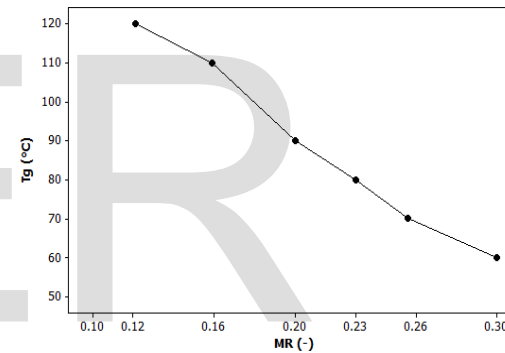


Fig.10. Glass transition temperature versus moisture ratio of potatoes

isotherm graphs. As reported by Mcminn and Magee [10] products having $a_w=0.2$ is most stable with respect to lipid oxidation, non-enzymatic browning, enzyme activity, and of course, the various microbial parameters. To keep the process in a glassy state and to produce better quality of dried products, glass transition temperatures as a function of moisture ratio give us a hint. It is recommended to process in a glassy state by adjusting the temperature. Rahman [14] reported the stability of food at a glassy state since below the glass transition temperature compounds involved in the deterioration reactions take time to diffuse over molecular distances and approach each other to react.

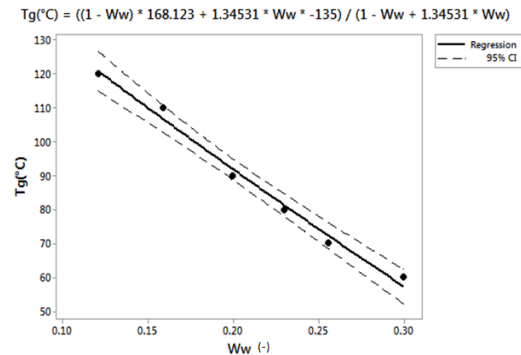


Fig.11 . Comparison between experimental and predicted values of the glass transition temperature versus Ww (MR) using Gordon–Taylor equation.

Comparison between experiment and predicted values of the glass transition temperature is presented in Fig.11. All the experiment values were laid in between dotted lines. This implies the experimental data satisfactory fitted to the Gordon-Taylor model at the confidence interval of 95%. The line represents the transition of the sample's state from glassy to rubbery. The region below and above the line represents the glassy and rubbery state respectively. Drying the sample within the glass state may give better quality and shelf stability. Roos,[13] reported Tg as indicator of the molecular mobility starting point of the solid matrix. The increase in temperature of a product above its Tg increase molecular mobility, and also affects diffusion of the matrix and results in an increase in rates of deterioration: enzymatic reaction, non enzymatic browning, and oxidation[13].

5. Conclusions

The GAB model was best for representing the relationship between the water activity and the equilibrium moisture content of potatoes. Optimum residual moisture contents of dried potato slices at a water activity of 0.2 were 4.2, 3.6 and 3.3% in (db) at temperatures of 60, 70 and 80 °C respectively. Therefore, according to the water activity concept in order to have a stable dried slice, to stop the drying process at moisture content of 4.2, 3.6 and 3.3% (db) were recommended for the samples dried at a temperature of 60, 70 and 80 °C respectively. However, according to the Tg concept, for the sample dried at a temperature of 60, 70 and 80 °C the molecular mobility of the matrix start at a moisture content of 30, 26, and 23% (db) respectively. This implies the molecular mobility of the matrix start before the sample attaining its optimum residual moisture content. This means, there is deterioration of quality due to high mobility of molecules when the sample dried above its glass transition temperature. Therefore, the combined knowledge of water activity, desorption isotherm, and glass transition temperature is required to produce quality and shelf stable product. Further research is required to relate hot

air drying of potato slices and glass transition temperature to improve the product quality.

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6. References

- [1]. W.A.M. McMinn and T.R.A. Magee, Moisture Sorption Isotherm Characteristics of Food Products: a Review. *Food and bio product processing*, 80(2), 118-129, (2002)
- [2]. M.S. Rahman, Food stability beyond water activity and glass transition: macro - micro region concept in the state diagram. *International journal of food properties*, 12: 726-740, (2009).
- [3]. S. S. Sablani, Evaluating Water Activity and Glass Transition Concepts for Food Stability. *Journal of Food Engineering*, 78, 266-271, (2007).
- [4]. C.T. Kiranoudis, Equilibrium Moisture Content and Heat of Desorption of Some Vegetables, *Journal of Food Engineering*, 20, 55-74, (1993)
- [5]. L., Emy, M. Dupas, and K. Jin, Glass Transition Phenomenon on Shrinkage of Papaya during Convective Drying. *Journal of Food Engineering*, 108(1), 43-50, (2012).
- [6]. I. Doymaz, and M. Pala, The thin-layer drying characteristics of corn. *Journal of Food Engineering*, 60, 125-130, (2003).
- [7]. M.S. Rahman, Food stability determination by macro-micro region concept in the state diagram and by defining a critical temperature, *Journal of Food Engineering*, 99 (4) 402-416, (2010).
- [8]. B.Sturm, W. Hofacker, and O. Hensel, Einfluss der fuhrung des trocknungs prozesses auf den trocknungsverlauf und die produkt-eigenschaften empfindlicher biologischer guter. Phd dissertation, Witzenhausen,(2010). (Dissertation)
- [9]. C. P. McLaughlin, and T. R. Magee, The Determination of Sorption Isotherm and the Isostatic Heats of Sorption for Potatoes. *Journal of Food Engineering*, 35(98), 267-280, (1998).
- [10]. W. A. M. McMinn., and T. R. Magee, Thermodynamic Properties of Moisture Sorption of Potato. *Journal of Food Engineering*, 60(2), 157-165, (2003).
- [11]. S. Chemkhi and F. Zagrouba, Characterization of Potato Slices During Drying: Density, Shrinkage, and Thermodynamic of Sorption, *International Journal of Food Engineering*, 7(3),1-15, (2011).
- [12]. N. Wang and J. G. Brennan, Moisture Sorption Isotherm Characteristics of Potatoes at Four temperatures. *Journal of Food Engineering*, 14, 269-287, (1991).
- [13]. Y. H. Roos, Water Activity and Physical State Effects on Amorphous Food Stability. *Journal of Food Process and Preservation*, 16:433-47,(1993).
- [14]. M.S. Rahman, Applications of Macro-micro Region Concept in the State Diagram and Critical Temperature Concepts in Determining the Food Stability. *Food Chemistry*, 132(4), 1679-1685, (2012).
- [15]. P.Liu, L.yu, and H.Liu, Glass transition temperature of starch studied by a high-speed DSC. *Journal of Carbohydrate polymers*, 2(77), 250-253, (2009).

- [16]. T. P. Labuza, A. Kaanane, and J. Y. Chen, Effect of Temperature on the Moisture Sorption Isotherms and Water Activity Shift of Two Dehydrated Foods. *Journal of Food science*, 50,385-391, (1985).
- [17]. W. Wolf, W. E. L. Spiess, and G. Jung, (1985). Standarization of Isotherm Measurements. In D.Simatos and J. L. Multon (Eds.), *Properties of Water in foods* (pp. 661-679). The Netherlands: Martinus Nijhoff.
- [18]. H.T. Addisalem and W. Hofacker, New method for glass transition temperature determination of potatoes. In the 20th International drying symposium, P2-32. Gifu, Japan, (2016). (Conference proceedings)
- [19]. M. S. Rahman, *Food Properties Handbook*; CRC Press: Boca Raton, FL, pp. 87-177, (1995).
- [20]. L.F. Moreno-Perez, J. H. Gasson-Lara, and E. Ortega-Rivas, Effect of low temperature-long time blanching on quality of dried sweet potato. *Drying Technology*, 14, 1839-1857, (1996).
- [21]. C. Van Den Berg, and S. Bruin, Water Activity and its Estimation in Food Systems: Theoretical Aspects. In *Water Activity: Influence on Food Quality* ed. L. B. Rockland & G. F. Stewart. Academic Press, New York, p. 45, (1981).
- [22]. C. R. Oswin, The kinetics of packing life. III. The isotherm. *Journal of Chemistry and Industry*, 65,419-23, (1946).
- [23]. G. Halsey, Physical Adsorption on Non-uniform Surfaces. *Journal of Chemistry and Physics*, 16, 931-937, (1948).
- [24]. S. Brunauer, P. H. Emmett, and E. Teller, Adsorption of Gases in multimolecular layer. *Journal of American Chemists Society*, 60, 309-319, (1938).
- [25]. R. J. Aguerre, C. Suarez, and P. Z. Viollaz, New BET Type Multilayer Sorption Isotherms. Part II. Modelling Water Sorption in Foods, *Lebemm. -wirs.u-technol.*, 22, 192-5, (1989).
- [26]. M. Gordon, and J. Taylor, Ideal copolymers and the second order transitions of synthetic rubbers. I. non-crystalline copolymers. *Journal of Applied Chemistry*, 81(1).89, (1952).
- [27]. G.P. Johary, A. Halbrucker, E. Mayer, The glass-liquid transition of hyperquenched water, *Nature*, 330(10), 552-553, (1987).
- [28]. E. J. Quirijns, A. J. B. Van Boxtel, W. K. P. Van Loon, and G. Van Straten, Sorption isotherms, GAB Parameters and Isotheric Heat of Sorption. *Journal of the Science of Food and Agriculture*, 85(11), 1805-1814, (2005).
- [29]. F. Kaymak-ertekin and A. Gedik, Sorption Isotherms and Isotheric Heat of Sorption for Grapes, Apricots, Apples and Potatoes. *Journal of Food science and Technology*, 37, 429-438, (2004).
- [30]. P.C Moyano, E. Troncoso, F. Pedreschi, Modeling texture Kinetics during Thermal processing of potato products. *J. Food Sci.*, 72, E102 - E107, (2007).
- [31]. D.S. Chung., and H. B. Post, Adsorption and desorption of water Vapor by Cereal Grains and their Products. Part I. Heat and Free Energy Changes of Adsorption and Desorption. *Transaction of the ASEA*, 10, 549-551, (1967).
- [32]. D. S. Chung, and H. B. Post, Adsorption and Desorption of Water vapor by cereal grains and their products. Part II. Development of the general isotherm equation. *Trans. ASAE*, 10, 552-5, (1967b).
- [33]. C.S. Chen, Equilibrium Moisture Curves for Biological Materials. *Trans. ASAE*, 14,924-6, (1971).
- [34]. H.A.Iglesias, and J. Chirife, Isotheric Heats of Water Vapor Sorption on Dehydrated Foods. Part I: Analysis of the differential heat curves. *Food Science and Technology*, 9, 116-122, (1976a).
- [35]. S. M. Henderson, A Basic Concept of Equilibrium Moisture. *Agric. Erg.*, 33, 29-32, (1952).

7. Appendices

Appendix Table. 1. models used to fit desorption isotherm of potatoes

Models	Equations	Temperatures	Material used	Authors
BET (Brunauer, Emmett & Teller, [24])	$M = \frac{M_o C a_w}{(1 - a_w) + (C - 1)(1 - a_w)a_w}$	30, 45, 60 °C	grapes, apricots, apples and potatoes	[29] >>
GAB (Guggenheim–Andersen–de Boer) (Van den Berg, [21])	$M = \frac{M_o C K a_w}{(1 - K a_w)((1 - K a_w + C K a_w)}$ $C = C_o \exp(\Delta H_c / RT)$ $K = K_o \exp(\Delta H_k / RT)$	>>	>>	>>
Chung–Pfof (Chung & Pfof [31])	$a_w = \exp(-k/RT \exp(CM))$	>>	>>	>>
_Modified Chung–Pfof (Chung & Pfof, [32])	$M = (-1/n) \ln\{(-(T+C) \ln a_w / k)\}$	>>	>>	>>
Chen (Chen, [33])	$a_w = \exp(k - C \exp(-bM))$	>>	>>	>>
Halsey (Halsey, [23])	$a_w = \exp(-K/m^n)$	>>	>>	>>
Modified Halsey (Iglesias & Chirife, [34])	$a_w = \exp(-\exp(KT+C)M^n)$	>>	>>	>>
Henderson(Henderson, [35])	$1 - a_w = \exp(-(KTM^n)$	>>	>>	>>
Iglesias–Chirife (Iglesias & Chirife, [34]) and	$\ln(M + (M^2 + M_{0.5})^{1/2}) = K a_w + C$	>>	>>	>>
Oswin (Oswin, [22])	$M = k(a_w / (1 - a_w))^n$	>>	>>	>>
GAB (Van Den Berg & Bruin, [21])	$M = \frac{M_o C K a_w}{(1 - K a_w)((1 - K a_w + C K a_w)}$	40,50,60, 70°C	Potatoes	[12] >>
Chen (Chen, 1971)[33]	$M = \frac{M_o C K a_w}{(1 - K a_w)((1 - K a_w + C K a_w)}$	>>	>>	>>

Oswin (Oswin, [22])	$M = A(a_w/(1 - a_w))B$	>>	>>	>>
Chung-Pfost (Chung & Pfost, [32])	$a_w = \exp(-A/T \exp(-BM))$	>>	>>	>>
Henderson (Henderson, [35])	$a_w = 1 - \exp(-AT M^B)$	>>	>>	>>
Halsey (Halsey, [23]) and BET(Brunauer <i>et al.</i> , [24])	$a_w = \exp(-A/ M^B)$ $M = \frac{M_o C a_w}{(1 - a_w) + (C - 1)(1 - a_w)a_w}$	>>	>>	>>
GAB[21]	$M = \frac{M_o C K a_w}{(1 - K a_w)((1 - (1 - C)K a_w))}$	30, 45, 60 °C	Potatoes	[5], [9]

Where C, K, A, and B are constants in the sorption isotherms models, a_w is the water activity, M_o is the monolayer moisture content (kg/kg, dry basis), M equilibrium moisture content kg/kg, dry base, T is the absolute temperature (K), R is the universal gas constant (J/mol K)

