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Cite as: AIP Conference Proceedings **2449**, 060022 (2022); https://doi.org/10.1063/5.0090830
Published Online: 01 September 2022

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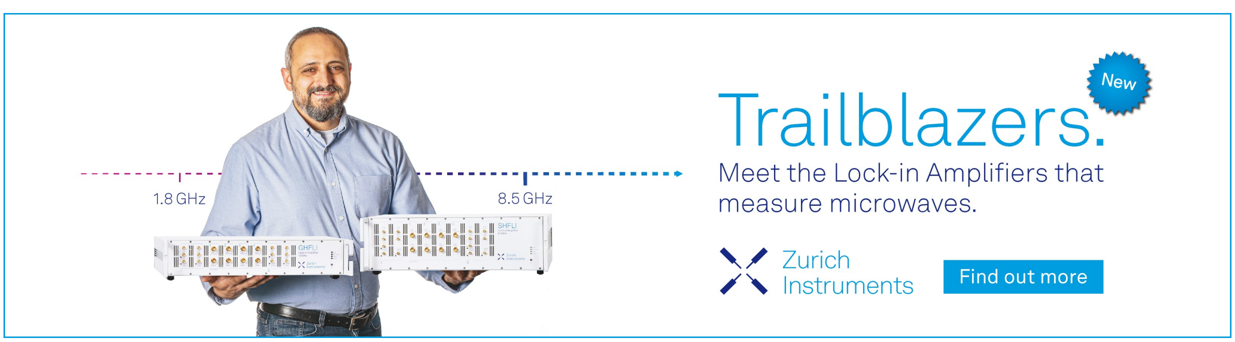

Sorption Isotherms and Characteristics of a Mixture of Brown Linseed and White Mulberry

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Abstract. The present paper models the mass-exchange processes of adsorption and desorption for a mixture of ground brown linseed (80%) and white mulberry (20%) which are bio-agricultural ingredients. The sorption capacity of the ready-made mixture was analyzed with reference to three temperatures – 10°C, 25°C and 40°C – and eight water activities in the 11% - 87% range. Via non-linear regression statistics, we modeled the modified three-parameter models of Chung-Pfost, Halsey, Oswin, and Henderson. Modified Halsey was found suitable for the description of the sorption characteristics of the ready-made mixture of brown linseed and white mulberry. The linear equations obtained from the linearization of the Brunauer-Emmett-Teller (BET) model helped in the calculation of monolayer moisture content (MMC) with test points for water activity $a_w < 0.5$ for adsorption in the 4.16% d.m. - 3.49% d.m. range and for desorpton in the 3.94% d.m. – 3.62% d.m. range.

INTRODUCTION

Diabetes is among the most prevalent diseases in the world affecting people of all age groups. It is a complex metabolic disorder greatly influencing carbohydrate metabolism. Diabetes is manifested by the heightened levels of glucose in the blood (blood glucose) and the occurrence of glucose in the urine. There are two types of diabetes: Type 1 diabetes and Type 2 diabetes. Type 1 diabetes is characterized by the improper production of insulin by the pancreas, which is why this type of diabetes is insulin-dependent. It affects 10 - 15% of the diabetics and its symptoms usually appear during childhood. Type 2 diabetes is characterized by the heightened cell sensitivity to the effects of insulin (insulin resistance), its secretion being slowed down or insufficient. In most cases, Type 2 diabetes is insulin-independent. This is also the most common type of diabetes since it affects 85 - 90% of the diabetics. Diabetics' diets play an important role in the maintenance of blood sugar levels within the normal range. The adequate intake of carbohydrates (sugars) is of greatest significance in the normalization of blood sugar levels. Some carbohydrate-rich food products raise blood glucose levels more quickly and unexpectedly. These are the foods having a high glycemic index (GI). Diabetics can very well control their blood sugar levels by opting for food with a low glycemic index (such as raw fruit and vegetables, legumes, spaghetti, wholegrain bread, oats, low-fat milk) [1-3].

10th International Scientific Conference "TechSys 2021" – Engineering, Technologies and Systems
AIP Conf. Proc. 2449, 060022-1–060022-6; https://doi.org/10.1063/5.0090830
Published by AIP Publishing. 978-0-7354-4397-6/$30.00

Linseed has become extremely popular among the proponents of healthy diets. Due to its being rich in dietary fiber and its low glycemic index, linseed may lower blood sugar levels and this is the reason why it is often consumed by Type 2 diabetes patients. It is also known as one of the most powerful vegetable foods on Earth. At present, linseed is incorporated into various types of food products, from cookies and sweets to porridge. Linseed is saturated with some of the major, most important nutrients which our bodies need in order to function properly, i.e. dietary fiber, proteins, magnesium, calcium, phosphorus, lignans, and omega-3 essential fatty acids. Omega-3 fatty acids, also called "good fats", have been proven to beneficially affect cardiac health. Lignans are phytoestrogens with significant antioxidant effects [4-7].

Recent years have witnessed the incorporation of extracts from the different parts of the mulberry plant into biologically active supplements (BAS) recommended for the regulation of carbohydrate and fat metabolism since they cleanse the stomach and expel waste products from the body. It is of great interest that the parts of the mulberry plant have a low glycemic index and can be consumed by diabetics. A study from 2007 reported that mulberry intake considerably affects blood sugar levels. In the medicine journal „Dovepress", researchers from India published the results from their studies of mulberry (*Morus indica*). They observed lower levels of blood sugar and glycogen in the liver, which testifies to the beneficial effects of the mulberry plant on diabetes patients. The berry of the plant is able to lower cholesterol levels and improve the ratio of "good" and "bad" cholesterol. As a whole, the berry fights well against metabolic disorders. It is an excellent source of protein, calcium, iron, vitamin C, vitamin K, dietary fiber, etc. The high concentration of the antioxidant resveratrol slows down the aging process. Mulberry can be consumed directly, as a filling of pastry, on in the form of juice, wine, and compote [8-10]. Recently, the ready-made mixtures have been increasingly used in the home for the preparation of various healthy snacks, smoothies, raw protein bars, sweets, etc. [11].

The extensive literature review made us draw the conclusion that the ready-made mixture of brown linseed and white mulberry can be consumed by people suffering from diabetes due to the low glycemic index of the ingredients and their high concentration of dietary fiber. That is why we decided to include the product in a project whose objective is the development of raw protein bars to be consumed by diabetics. In the literature review, we did not find instances of any research on the sorption characteristics of such a mixture. The analysis of sorption characteristics gives important information on the adequate selection of the regimes of processing, storage, and transportation of food products [12-13].

MATERIALS AND METHODS

Raw Materials

Ground brown linseed and white mulberry – purchased in Bulgaria by "Internet café-BG" Ltd, packed by "Zoya bg Organic Shop".

Methods

This experiment was based on the static gravimetric method as improved, accepted and standardized for food products by the Project COST 90. For the description of the sorption isotherms, we used the modified three-parameter models of Oswin, Chung-Pfost, Halsey, and Henderson. In order to determine the coefficients (*A*, *B* and C*),* we used a non-linear regression program "*Statistica*" following the least squares method ("*Nonlinear estimation*" procedure) [14]. Mean relative error, standard deviation and distribution of residuals were applied as criteria for the evaluation and comparison of the models. The Brunayer-Emmett-Teller (BET) model was linearly transformed in order to calculate the values of monolayer moisture content (MMC). MMC can be considered as a critical point in the sorption isotherm and its identification is very important in the case of a product undergoing storage [15-16]. A number of studies of Durakova et al., (2021); Durakova, et al. (2020); Menkov et al., 2009; Bogoeva and Durakova, (2020); Farahnaky et al., (2016) [11-12; 14; 17-18] have described in detail the methods used in the analysis of sorption characteristics. All tests were conducted in triplicate runs.

RESULTS AND DISCUSSION

The nutrient composition of the ready-made mixture of ground brown linseed (80%) and white mulberry (20%) per 100g of product was as follows: energy 2343kJ/563kcal; fat – 31g, of which saturated 4g, of which omega - 3 fatty acids 14.9g; carbohydrates 42.7g, of which sugars 8.4g; fiber 23.4g; protein 16.4g.

The equilibrium moisture content values of the mixture, obtained for adsorption and desorption, are shown in Tables 1 and 2. In order to conduct the experiment, the product with an initial moisture of 13.66% d.m. for adsorption was pre-dried over P_2O_5 to a moisture of 7.73% d.m., whereas for desorption it was humidified over H_2O_Δ to 15.75% d.m.

TABLE 1. Equilibrium moisture content M, % d.m. for adsorption at different temperatures t (°C) and water activity a_w

Sel		**10°C**			**25°C**			**40°C**	
	a_w	**M***	**sd****	a_w	**M****	**sd****	a_w	**M****	**sd****
LiCl	0.113	5.696	0.13	0.113	4.150	0.21	0.113	3.538	0.20
CH_3COOK	0.234	6.207	0.27	0.234	4.764	0.05	0.234	3.709	0.13
$MgCl_2$	0.335	6.472	0.12	0.335	5.469	0.12	0.335	4.213	0.10
K_2CO_3	0.431	7.519	0.09	0.431	6.229	0.15	0.431	5.040	0.16
$MgNO_3$	0.574	8.209	0.01	0.574	8.003	0.14	0.574	7.670	0.12
NaBr	0.622	8.407	0.21	0.622	8.025	0.13	0.622	7.707	0.13
NaCl	0.757	13.589	0.05	0.757	12.576	0.08	0.757	11.643	0.15
KCl	0.868	23.016	0.23	0.868	17.251	0.07	0.868	17.188	0.08

* Mean of three runs, ** Mean deviation of three runs

TABLE 2. Equilibrium moisture content M, % d.m. for desorption at different temperatures t (°C) and water activity a_w

Sel		**10°C**			**25°C**			**40°C**	
	a_w	**M***	**sd****	a_w	**M****	**sd****	a_w	**M****	**sd****
LiCl	0.113	4.612	0.22	0.113	4.354	0.20	0.112	3.665	0.15
CH_3COOK	0.234	5.487	0.05	0.225	5.013	0.15	0.201	4.926	0.15
$MgCl_2$	0.335	6.149	0.14	0.328	5.980	0.13	0.316	5.840	0.12
K_2CO_3	0.431	7.714	0.13	0.432	7.429	0.07	0.432	6.391	0.14
$MgNO_3$	0.574	9.239	0.16	0.529	7.867	0.14	0.484	6.965	0.16
NaBr	0.622	12.634	0.16	0.576	9.437	0.14	0.532	9.199	0.09
NaCl	0.757	13.757	0.12	0.753	12.530	0.05	0.747	11.261	0.13
KCl	0.868	18.389	0.06	0.843	16.540	0.17	0.823	15.509	0.16

* Mean of three runs, ** Mean deviation of three runs

For both processes, we observed the tendency, pointed out in plenty of studies, that the increase in temperature leads to the decrease in equilibrium moisture content values under constant hygrothermal conditions (water activity) [19-21]. For adsorption, the greatest decrease in percentages was manifested at water activity of 0.868 – 5.828%, the slightest decrease being at a_w = 0.574 - 0.539%. For desorption, the analysis showed that the most considerable decrease was at a_w = 0.622 – 3.435%, the lowest decrease being at a_w = 0.335 – 0.309%. As regards the other water activity values, for both processes the decrease in percentages of equilibrium moisture content, following the increase in temperature, fell within the range of about 1-2%.

Figure 1 compares the obtained equilibrium sorption isotherms for adsorption and desorption at the temperature of 25°C.

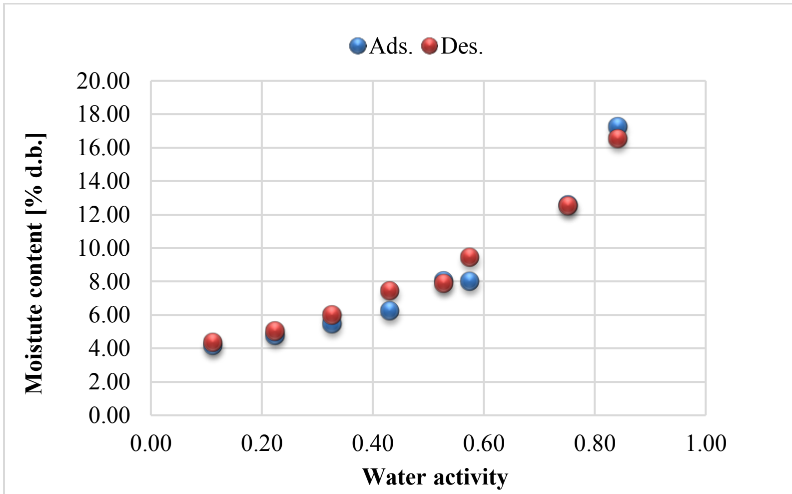

FIGURE 1. Comparison of equilibrium sorption isotherms at 25°C

The figure illustrates that the isotherms belong to Type III according to the classification of Brunauer et al. We observe hysteresis, which confirms the results of other researchers' studies on analogical products [14-17].

As a result of modeling the sorption isotherms of the mixture under study, we obtained the coefficients (*A*, *B* and *C*) of the modified three-parameter models, the mean relative error (*P*, %), the standard deviation (*SEM*) and the distribution of residuals. The results obtained are shown in Table 3 for adsorption and in Table 4 for desorption.

TABLE 3. Coefficients of the models (A, B, C), mean relative error (*P*, %) and standard deviation (*SEM*) for adsorption.

Model	A	B	C	*P*	*SEM*	Residuals
Oswin	8.926	-0.049	0.402	13.97	1.90	non-arbitrary
Halsey	**3.349**	**-0.014**	**1.674**	**9.94**	**0.95**	**arbitrary**
Henderson	0.0003	49.531	1.694	17.82	2.51	non-arbitrary
Chung-Pfost	990.817	239.949	0.212	18.21	2.34	non-arbitrary

TABLE 4. Coefficients of the models (A, B, C), mean relative error (*P*, %) and standard deviation (*SEM*) for desorption.

Model	A	B	C	*P*	*SEM*	Residuals
Oswin	9.633	-0.055	0.377	7.69	0.89	non-arbitrary
Halsey	**3.530**	**-0.008**	**1.792**	**6.14**	**0.88**	**arbitrary**
Henderson	0.0003	47.435	1.641	12.57	1.15	non-arbitrary
Chung-Pfost	600.515	0.222	109.788	10.83	1.17	non-arbitrary

Statistically processing the results in the tables, it becomes evident that the lowest values of P = 9.94% for adsorption and P = 6.14% for desorption, SEM = 0.95 and SEM = 0.88, for the two processes respectively, and arbitrary distributions of residuals were obtained in the case of the modified Halsey. The analysis makes us recommend the modified Halsey for the description of the sorption isotherms of the ready-made mixture of ground brown linseed and white mulberry.

The linearization of the Brunauer-Emmett-Teller (BET) model makes it possible to calculate monolayer moisture content values (MMC) with test data for $a_w < 0.5$ [11-12, 15-16]. The linearization of the model and the equations obtained for all three temperatures can be seen in Figures 2 and 3, for adsorption and desorption respectively.

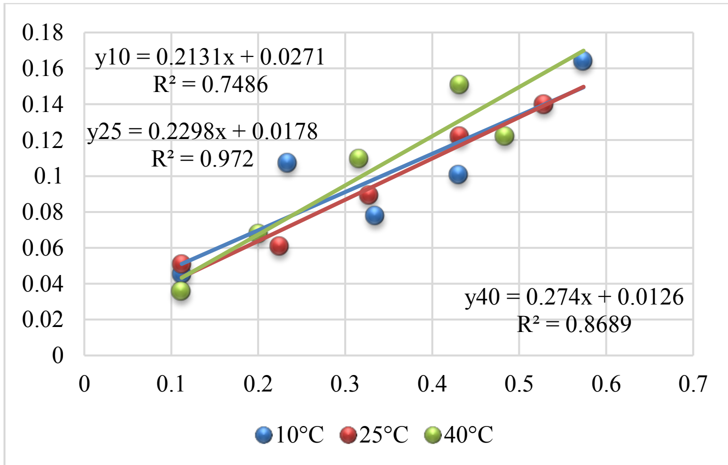

FIGURE 2. Linearization of the BET model for adsorption

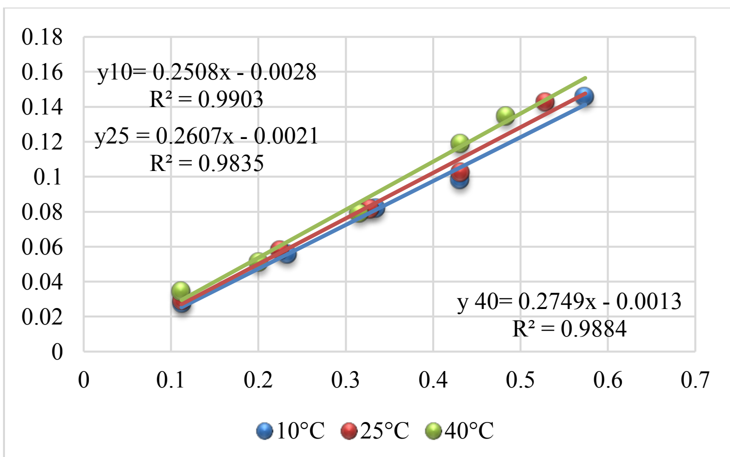

FIGURE 3. Linearization of the BET model for desorption

The calculated MMC values for all three temperatures – 10°C, 25°C and 40°C – are presented in Table 5.

TABLE 5. BET monolayer moisture content, % d.m. at different temperatures *t*.

t (°C)	Adsorption	Desorption
10	4.16	3.94
25	4.04	3.81
40	3.49	3.62

The analysis of the results demonstrates that the values range from 4.16% d.m. to 3.49% d.m. for adsorption and from 3.94% d.m. to 3.62% d.m. for desorption. We can see that the increase in temperature is coupled with the decrease in MMC: for adsorption the moisture decreases by about 0.67% d.m. in the 10°C – 40°C range, whereas for desorption this decrease is by approximately 0.32% d.m. for the same temperature range.

CONCLUSIONS

We analyzed the hygrothermal equilibrium between humid air and the mixture of ground brown linseed and white mulberry for the temperatures of 10°C, 25°C, and 40°C and a_w = 0.10÷ 0.87. We obtained the equilibrium sorption isotherms for adsorption and desorption. It was discovered that the temperature affects the sorption capacity of the mixture: at a constant water activity, the increase in temperature leads to the decrease in equilibrium moisture content. It was observed that the sorption isotherms belong to Type III according to the classification of Brunauer et al. On the basis of statistical processing, in accordance with the accepted criteria, we identified and suggested the modified Halsey for the description of the sorption isotherms of the mixture. The study obtained the MMC values with test points for water activity $a_w < 0.5$: for adsorption in the 4.16% d.m. - 3.49% d.m. range and for desorption in the 3.94% d.m. – 3.62% d.m. range. It was determined that the increase in temperature is coupled with the decrease in MMC values.

ACKNOWLEDGMENTS

This study was part of the Scientific Research Fund "FS N11/20-H", project director: Assoc. Prof. PhD Albena Georgieva Durakova, University of Food Technologies – Plovdiv, Bulgaria.

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