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The Influence of a Static, Homogeneous Magnetic Field on the Sorption Properties of Soybean Meal During Maritime Transport

A. Ocieczek, A. Kaizer & Z. Otremba
Gdynia Maritime University, Gdynia, Poland

ABSTRACT: Providing safety and maintaining high quality of dry cargo, transported by sea, is associated with the necessity of taking into consideration their specific property, which is hygroscopicity. Susceptibility to the impact of water, which also occurs in vapour state, concerns mainly dry cargo, which are organic matter, containing carbohydrates and protein in their composition. This is because these substances have strong connection with water. The example of a bulk cargo often transported by sea is soybean meal, which is mainly produced in the USA, Brazil and Argentina. Due to its economic importance, the quality of soybean meal, which is globally used in the animal nutrition (poultry and swine), remains an important research issue. This product is obtained by subjecting the soybeans to cracking and dehulling processes, in order to facilitate the extraction of the oil.
Water absorption of soybean meal causes reactions taking place in it, which leads to the changes in its chemical composition and, consequently, also in its nutritional values. Moreover, increasing the water content, leading to the increase of water activity, may significantly deteriorate the microbiological safety of the meal. Therefore, the research was undertaken to determine whether the sorption properties of soybean meal will change due to the influence of a static, homogeneous magnetic field.
This aim has been achieved by determining and comparing the water vapour adsorption isotherms. The comparison of the isotherms determined under normal conditions and under the influence of a static, homogeneous magnetic field with an induction of 10 mT has been made on the basis of empirical data. Furthermore, using the Brunauer, Emett and Teller equation (BET), the monolayer and the energy constant of the sorption process have been estimated. The isotherms were determined at 20°C. The study lasted 9 days. Desiccators with aqueous supersaturated solutions of substances and a generator of a static magnetic field were used in the research.
The obtained results have indicated that the influence of the magnetic field is a factor that causes the differentiation between the sorption properties of soybean meal expressed in the volume of the monolayer and the energy associated with the sorption phenomenon. The inferred findings show, that the magnetic field has an impact on the course of the sorption phenomenon in organic samples, and may determine the stability of the cargo during long-term maritime transport.

1 INTRODUCTION

Soybeans are one of the most important crops, covering about 6% of the world's arable land. It has been observed since the 1970s, that the soybean production area has higher growth rate than any other major crop. Hartman et al. [13] highlighted a number of important abiotic and biotic factors, which may be critical elements that potentially endanger the soybean production by direct impact on reduction of crop yields and / or quality of soybean seeds. Critical abiotic factors include extremely unfavorable soil properties, temperature fluctuations and the availability of water for agricultural production, which may limit the production volume, but also could influence the quality of the raw material produced. On the other hand, critical biotic factors are usually geographically and environmentally determined by influencing the type of specific and usually dominant pathogens and pests. However, due to the lack of advanced technologies, a wide range of appropriate soybean management strategies has not been widely available yet, the development in this area is in progress. For example, new soybean varieties enable to cultivate them, even in soil conditions which have been considered as unsuitable for long [23]. This currently occurs in Argentina and Brazil, in areas which had been formerly inadequate for soybean cultivation. Previously, it had been primarily American soybean farmers, who had responded to the growing global demand for protein feed for the meat and poultry sector [6]. Taking the above into considerations, it can be assumed that in some time perspective Europe may join China and Asian countries, which have also contributed to the development of the global soybean market. This, particularly, should translate into the promotion of sustainable development, in which a significant role may be played by the reduction of the necessity of bulk transport of this raw material or its products [21]. In conclusion, it is likely that both the crop yields of soybean and the area under its cultivation will increase, and therefore there will be the, associated with these, significant increase in the production of soybean meal and oil [24].

Soybean can be, and is, consumed by humans as a food. For example, in China it is now the main ingredient for the production of food products such as tofu and soy milk. However, it should be emphasized, that its consumption by humans is still low, in comparison to the level of its use in the production of fodders, which actually determines the value of international trade in this raw material. At the same time, it should be noticed that it is the rapid growth of world population and, consequently, of many economies, especially in Asia, that has led to an increased demand for animal protein and vegetable oil. Therefore, it can be assumed that the international soybean trade will continue to develop, at least in the near term.

Global trade in oilseeds includes many raw materials, such as: rapeseed, sunflower and cotton, which could potentially be an alternative to soybeans. However, the specific nutritional quality requirements for protein meal, for edible vegetable oil, and for oil used for a production of biofuel, determine the ratio of various oilseeds in the market, depending on the demand for products made from these seeds. Therefore, trade, but not only it, in particular oily feedstock, is conditioned primarily by the development of industry. International trade has been expanding rapidly, since modern economies became highly industrialized. This is because of the fact, that there is a positive correlation between trade and development [14]. Nevertheless, globalization has not always improved development, taking into account social variables such as employment and poverty [15]. An important problem is also, how the trade in oilseeds affects food security both in the countries of their origin and outside them [25]. In addition, the impact of the technical and natural effects of oilseed trade on climate change, is also increasingly taken into account [35]. In this context, the issue of maintaining the safety and good quality of bulk cargo, which are both soybeans and soybean meal, is especially important. The case when the reduction of the safety and/or quality level, as well as the destruction of the raw material and the product, happens, should be considered not only as a direct loss, but also as the environmental burden connected with their production [3, 37].

2 THREATS TO THE SAFETY AND QUALITY OF SOYBEAN MEAL IN TRANSPORT

Soybean meal is one of the most commonly used ingredients in compound feed. The growing demand for this product, determines more requirements for the safety during transport processes. In transport processes, soybean meal occurs in the form of a solid bulk cargo. Due to its inherent properties, it is classified as a special cargo. It is categorized, according to the IMDG code, as a dangerous good of class 4.2 [7].

The influence of external factors on changes in the quality characteristics of soybean meal has an important role in appearance of threats during the transport processes of this type of cargo. Maintaining the safety and quality of soybean meal during transport depends on the conditions of storage, handling and transport. In studies, which concerns the changes in the quality of soybean meal during maritime transport, the main external factor taken into account in the research, is the ambient humidity [7]. This parameter is an important element of the environment, and moreover it is an important factor of the sensitivity of the cargo, which is a soybean meal. Due to the hygroscopicity of soybean meal, it absorbs water vapor from the environment, and hence the transport and technological quality features of its change. These properties are for example: kinetic angle of repose, size of molecule, bulk density, porosity. Therefore, the absorption of water vapor by soybean meal, changes the essential characteristics of this cargo at particular stages of the transport chain. Fortunately, the correlation between the changes in the transport-technological qualities of soybean meal and the occurring under the influence of air humidity changes of water content in soybean meal, has been identified. In relation to the above, it has been discovered that under the influence of surrounding the cargo humid air, in which the transport processes take place, and depending on the degree of comminution of soybean meal grains, there is a significant differentiation in transport and technological qualitative characteristics [7].

Weighing all above considerations, it could be assumed, that searching for innovative methods, which will enable to stabilize the microbiological safety and the quality characteristics of soybean meal as a cargo under the conditions of its exposure to water vapor, is a reasonable performance. The phenomenon of water vapor sorption on the surface of organic samples, e.g. soybean meal, may have different kinetics (different directions and different dynamics), which depends on their properties related to the chemical composition and physical structure [7]. It is also connected with the difference between the water activity in the sample and the relative vapor pressure of the surrounding air, and also it results from the nature of the phenomenon taking the form of adsorption or desorption [12, 17]. The sorption phenomenon is also related to the extent of ordering of the matrix in the solid matter subjected to the interaction with water vapor.

Substances characterized by a relatively high homogeneity (e.g. starch) do not undergo any changes in the sorption mechanism due to the water vapor present in the surrounding atmosphere [22]. On the other hand, amorphous substances (e.g. powdered milk) are prone to a change in the sorption mechanism associated with structural changes in components, which includes imbibition, growth of the mobility of protein chains, and revealing new sorption centers [27]. As a result of the structural changes of the components, the sorption rate is constantly high or even increases periodically. This is because of the fact, that sorption involves an increasing number of active centers available for water molecules. In addition, after absorbing a certain amount of water, specific for each type of substance, amorphous components can turn into a crystal [31], which, in the range of average values of relative humidity of the atmosphere, is able to absorb and retain only small amounts of water. The transformation of the amorphous component into a crystalline solid causes a modification of the sorption mechanism.

3 THE ADVANCEMENT OF THE RESEARCH ON THE INFLUENCE OF THE MAGNETIC FIELD ON THE SURFACE PHENOMENA

The influence of the magnetic field on various types of biological and physicochemical processes has been studied so far in terms of its usefulness in environmental engineering, for example in the crystallization of calcium carbonate [9], in the water purification [1, 2], in the coagulation and sedimentation of colloid particles [16, 36], and in the wastewater treatment [18, 38]. The research results have also indicated, that the magnetic field affects the dynamics of some reactions occurring in food during its storage [20]. However, the most spectacular are the reports predicating that the magnetic field influences the proper functioning of living organisms [10].

The studies on the impact of the magnetic field on the course of surface phenomena are definitely rare. In the paper prepared by Ocieczek and Otremba [28], the existence of the influence of the heterogeneous, static magnetic field on the course of the phenomenon of water vapor desorption, induced by an increase in ambient temperature, from the surface of starch particles, and the practical consequences associated with it, was demonstrated. It was proven that the magnetic field increases the value and rate of water desorption from the starch surface. Although the mechanism of the course of the desorption process in the presence of a magnetic field had not been fully recognized yet, the results of this work have begun the research aiming for creation of the base for forecasting the changes occurring in food under different conditions, even different from those on Earth. This, in consequence, may be significant in the future, in consideration of the developing exploration of extraterrestrial space. What is more, this work highlighted that the phenomenon of desorption should be investigated in terms of its role in the effectiveness of the devices created for dewatering samples, which are sensitive to high temperatures. On the other hand, the work of Ocieczek and Otremba [30] includes an assessment of the effect of a homogeneous, static magnetic field on the phenomenon of water vapor sorption, in this case induced by the influence of the environment with a humidity of 7% and 75%. It has been found that the static and homogeneous magnetic field increases the rate of water adsorption by the tested organic substances, especially in the initial phase of this process. In addition, it has been discovered that the magnetic field affects the sample-atmosphere dynamic equilibrium, namely with the impact of magnetic field it is higher. On the other hand, the course of water desorption from organic substances in the magnetic field is similar to this process in the absence of the field. At the same time, no grounds have been found to conclude, that the magnetic field is not involved in this process. It has been indicated, that it is more likely that the interference of the magnetic field in the used research model, may take place through kinetically mutually competing processes. The above mentioned work also contained elements of the research on the statics of the sorption phenomenon, which has become the inspiration for the studies presented in this article. In the next paper [29] the same authors discussed the effect of a homogeneous, static magnetic field on the direction, dynamics and scope of adsorption and desorption of water vapor through the solid matrix at two different temperatures. These studies concerned the kinetics of the sorption phenomenon and the aim of the system to reach the dynamic equilibrium. The adopted research model was an extension of the assumptions of the work described above [30] and enabled to find that the impact of the magnetic field on the kinetics and the scope of the surface phenomenon is statistically significant, and this statement may be rudimental for the organization and management of technological processes and storage.

Therefore, the aim of this work is to develop the knowledge concerning the influence of the magnetic field, this time, on the statics of the sorption phenomenon. The essence of the study was to verify the assumption of the existence of an influence of a homogeneous, static magnetic field with an induction of 10 mT on the equilibrium state of the tested system at a constant temperature 20°C. The study was carried out parallelly: under control conditions and under the influence of a homogeneous, static magnetic field. As a result of the research, a state of dynamic equilibrium between the tested samples of soybean meal and the external environment with a humidity ranging from 7 to 98% was identified. In accordance with that, it was hypothesized that the influence of a homogeneous, static magnetic field changes the state of dynamic equilibrium of the examined system, in relation to its aiming to reach maximum disorder and minimum energy. The study included the determination and comparison of water vapor sorption isotherms, and the indication of the parameters of the Brunauer, Emmett and Teller equation by adjusting them to the set of empirical data, describing sorption isotherms.

4 RESEARCH MATERIAL, RESEARCH METHODS AND ORGANIZATION OF THE EXPERIMENT

The research material was soybean meal, which is a source of protein and valuable amino acids, used as animal feed. The research material was characterized by determining the parameters critical for stability during transport and storage, such as water content and water activity. In addition, bulk and tapped density of soybean meal was determined. The main element of the research was the determination of water vapor sorption isotherms describing the state of dynamic equilibrium, and the indication of the parameters of the BET model.

The water content of the tested material was determined by drying. About 1 g of the test product was weighed into the weighed weighing vessels with an accuracy of 0.0001 g. They were then placed in a dryer at 105°C and dried to obtain constant weight. The determination was carried out in three parallel attempts. The water content were calculated in grams per 100 grams of dry matter.

Water activity (aw) at 20°C was determined with an accuracy of ±0.003 in the AquaLab apparatus (ver. AS4 2,14.0 2017, Series 4TE and 4TEV Decagon Devices, Inc., Pullman, WA, USA).

Density, which defines the typical of bulk materials ratio of the mass per unit volume, was determined in two variants. Determination of the bulk density consisted in weighing a sample with a mass of 100 g and transferring it into a measuring cylinder in order to define the volume occupied by this mass. The essence of the test was to insert dry matter into the cylinder in such a way that it would not be compacted. On the other hand, the determination of the tapped density, consisted in subjecting the sample, which was prepared for measuring the bulk density, to mechanical compaction. It was achieved by exposing the cylinder with the sample to the vibrations resulting from gentle hitting on a flexible surface for 60 seconds. As a result of the 60-second vibration influence on the soybean meal sample placed in the cylinder, it became denser, which manifested itself in a reduction in the volume occupied by the sample, which was read on the cylinder scale. The tapped density was always characterized by a higher value than the bulk density. The determination was carried out in three parallel attempts.

Sorption isotherms were determined by the referenced static-desiccator method. The time for the samples to reach the state of dynamic equilibrium was set at 9 days, on the basis of a previously conducted reconnaissance experiment, which had determined the minimum time necessary to reach the dynamic equilibrium between the environment and the surface of soybean meal [30]. 1 g samples of soybean meal, weighed with an accuracy of 0.0001 g, were placed in 11 desiccators containing supersaturated solutions of the substance (NaOH - 0.0698; LiCl - 0.1114; CH_3COOK - 0.2310; $MgCl_2$ -0.3303; K_2CO_3 - 0.4400; $Na_2Cr_2O_7$ - 0.5480; KJ - 0.6986; NaCl - 0.7542; KCl - 0.8513; KNO_3 - 0.9320; $K_2Cr_2O_7$ – 0,98) with a water activity from 0.07 to 0.98 [11]. In desiccators with an activity higher than 0.6, to eliminate the risk of mold growth, thymol was placed. Measurements of the mass and water activity of the tested samples were carried out each time after the end of time of their exposure to the environment. The experiment was conducted in a climatic chamber with a temperature at 20°C ± 1°C. The determination in each of the desiccators was carried out in three parallel attempts. Then the procedure was analogous, but the desiccators with the samples of soybean meal were placed in a homogeneous, static magnetic field with an induction of 10 mT (Fig. 1.).

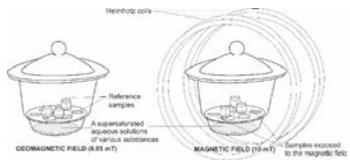

Figure 1. Experimental setup: desiccator with reference samples in geomagnetic field 0.05 mT (left), desiccator between Helmholtz coils, which generated static homogeneous magnetic field 10 mT (right)

The static MF generator has been designed and constructed at the Physics Department of Gdynia Maritime University. It consists of two identical Helmholtz coils arranged parallel to each other. The electric current in the coils (14 amps) required to generate static MF 10 mT is provided by two laboratory switching mode power supplies HCS-3602 (Manson, China). The heat from the coils is discharged by means of circulating water through the flow cooler (Titan 4000, Aqua Medic, Germany). Generator is equipped with AC gaussmeter GM-2 (AlphaLab Inc., USA) that measures and adjusts the value of magnetic induction.

The significance of the differences between the average water content and water activity in the tested samples after their incubation under control conditions and under the influence of a homogeneous, static magnetic field, was determined using the Student's t-test. Earlier, the variability assessment (variance estimation) in the compared groups had been performed, using the Fisher's exact test.

In order to determine the differences in the sorption properties of the tested samples of soybean meal, on the basis of empirical results, their transformation has been carried out so as to identify and compare the parameters of the BET model as:

$$v = \frac{v_m C a_w}{(1-a_w)[1+(C-1)a_w]} \quad (1)$$

where:
a_w – water activity (–); v – equilibrium water content (g H_2O/100g d.m.); v_m – water content in the monolayer (g H_2O/100g d.m.); C – energy constant [11, 31].

The parameters of the BET equation were determined numerically, using non-linear regression and the Monte Carlo algorithm. The minimization of the sum of squared residuals was used as the objective function. The calculations were made in the Excel 2010 spreadsheet. The values of the standard errors of the determined parameters were estimated using the SolverAid macro command based on the Hessian matrix [39].

5 RESULTS AND DISCUSSION

Skimmed soybean meal is the material remaining after the extraction of oil from soybean flakes. Soybean meal is considered as a dry material (12% d.m.), because it is in the form of solid particles [26]. Soybean meal is also an heterogeneous mixture of particles, which differ in size and shape. These particles are subject to intermolecular interactions which determine the cohesion of the material, and the cohesion of the material plays an important role in the transport process [7].

The parameters for describing cohesion are bulk density and tapped density. As a result of the research, it was found that the soybean meal has a bulk density of 0.606 ± 0.010 g / cm^3 and a tapped density of 0.666 ± 0.021 g / cm^3. This means that under the influence of vibration, soybean meal becomes denser, which increases its density by more than 9%. This fact is important, influencing both its mechanical and thermal properties as a cargo. In the studies by Drzewieniecka et al. [7] it has also been defined that water content is a factor that significantly influences the bulk density of soybean meal. In the case of soybean meal with 10% water content, the bulk density was 0.593 g / cm^3 and it was higher in comparison to dry meal (at 0% of water), in which the bulk density was 0.584 g / cm^3. The growth of the density of soybean meal due to the increase of water content and vibrations may lead to self-heating or even to self-ignition.

Soybean meal is a hygroscopic cargo. Ambient air humidity associated with daily and seasonal fluctuations affects the changes in the water content in soybean meal. This concerns especially the maritime transport, where modifications in these parameters are additionally caused by changes of climatic zones. Therefore, another important parameter characterizing the tested soybean meal was the water content and water activity. It was found that the water content was at 11.8567 ± 0.1076 g / 100 d.m. This value can be considered as relatively low and appropriate to ensure its storage stability in the transport process, provided that the risk associated with the absorption of water from the environment is eliminated [26]. Equally important factor is the water activity, which determines changes in dry mass and their dynamics during storage. This parameter is mainly determined by the water content, but its level is also influenced by interactions between the surface of the object and water, by condensation of water vapor in capillaries, and by the concentration and type of water-soluble substances [5]. The water activity was found to be at 0.4755 ± 0.0018. This value can be considered as relatively low, because it ensures the microbiological stability of the meal [34]. This statement results from the fact, that microbes have the ability to reproduce if the water activity is higher than 0.6 [32]. Therefore, the water present in the examined meal cannot increase the level of microbial contamination.

In homogeneous bodies, such as liquids, the intermolecular forces inside the phase balance each other. Only particles on the surface of the material are subject to unbalanced forces, which leads to the induction of sorption. In inhomogeneous bodies such as soybean meal, no balance of forces should be expected, even inside the mass. However, the energy state of the surfaces of individual particles is always higher than the energy state of the interior [8]. Products with a developed surface, such as meal, are characterized by high surface energy, which significantly affects its interaction with the environment. On the surface of the product there are processes leading to the saturation of unbalanced forces and reaching the state of minimum energy. This, thus, leads to a densification of the particles of the phase being in contact with the surface.

Although the phenomenon of water vapor sorption on the surface of organic samples goes on with different kinetics, it leads to a state of dynamic equilibrium, depending on the ambient temperature. Therefore, the range of the sorption process is reflected in the static description of this phenomenon, which is the sorption isotherm. Each point on the sorption isotherm is reached as a result of a dynamic process with different specificities related to more or less complex mechanisms [17]. Most often, the water vapor sorption isotherms determined for biological material have a sigmoidal shape with two characteristic inflection points [31]. First of them is in the range of low water activities and corresponds to the formation of the monomolecular layer. The second one is in the range of high water activities and indicates the initiation of the capillary condensation phenomenon. Table 1 summarizes the empirically obtained results, which describe the characteristic for the sorption isotherm dependencies between the water content and water activity in the entire range.

Identification of the significance of the influence of the magnetic field on the values of water content and water activity in the tested samples was made using the Student's t-test, which was preceded with an assessment of the variability in the compared groups with the use of Fisher's exact test. The results are summarized in Table 2.

Table 1. Isotherms of the water vapor sorption on the surface of soybean meal particles determined under control conditions and under the influence of a homogeneous, static magnetic field with an induction of 10 mT

L.p.	Control conditions		Conditions with the influence of a magnetic field	
	Water activity±SD	Water content±SD	Water activity±SD	Water content±SD
1.	0.0486 ± 0.0073	5.2863 ± 0.0152	0.0760 ± 0.0016	5.8567 ± 0.3749
2.	0.1210 ± 0.0010	7.8056 ± 0.0604	0.1197 ± 0.0017	7.3297 ± 0.0973
3.	0.2348 ± 0.0014	10.0782 ± 0.0158	0.2361 ± 0.0005	10.0702 ± 0.0467
4.	0.3382 ± 0.0023	11.1321 ± 0.0440	0.3310 ± 0.0012	10.9741 ± 0.0471
5.	0.4155 ± 0.0008	12.3417 ± 0.0403	0.4238 ± 0.0017	12.4136 ± 0.0414
6.	0.5059 ± 0.0025	13.3563 ± 0.0618	0.5376 ± 0.0007	13.3052 ± 0.0323
7.	0.6701 ± 0.0023	14.6235 ± 0.1754	0.5934 ± 0.0019	13.6217 ± 0.0333
8.	0.7383 ± 0.0006	16.2498 ± 0.1170	0.7445 ± 0.0022	16.3769 ± 0.1800
9.	0.8153 ± 0.0028	19.9768 ± 0.3502	0.8227 ± 0.0033	20.2717 ± 0.2417
10.	0.9228 ± 0.0049	30.7746 ± 0.9779	0.9444 ± 0.0009	33.2165 ± 0.5210
11.	0.9485 ± 0.0024	35.7387 ± 0.3564	0.9535 ± 0.0030	37.1627 ± 1.5803

Statistical evaluation of the equilibrium water content and water activity in soybean meal samples subjected to the influence of water vapor under the control conditions, and under the influence of the magnetic field, indicated the existence of the impact of this field on the amount and condition of water in the tested samples. Desiccators with a statistically significant effect of the field on water content and water activity are marked in bold. At the same time, it should be noted that the influence of the magnetic field had a greater impact on the condition of water expressed by its activity than on the water content. Therefore, it can be assumed that the performed observation was the result of the fact that the magnetic field influenced not only the condition of water contained in the soybean meal but also that which was contained in supersaturated solutions of substances in desiccators. Thus, the achieving of the equilibrium state, examined with the use of sorption isotherms, was the result of phenomena that could strengthen or weaken each other. Ocieczek and Otremba [29, 30] had reached similar conclusions in their research on the kinetics of the sorption process.

Table 2. The results of the significance of the influence of the magnetic field on the water content and water activity in the state of dynamic equilibrium with the environment

L.p.	Water content n=3		Water activity n=3	
	F-test	P-value	F-test	P-value
1.	0.0033	0.0580	0.0904	**0.0031**
2.	0.5568	**0.0020**	0.5342	0.3312
3.	0.2044	0.7927	0.2161	0.1750
4.	0.9308	**0.0132**	0.4216	**0.0093**
5.	0.9745	0.0975	0.3433	**0.0017**
6.	0.4286	**0.0027**	0.1570	**2.8424E-05**
7.	0.0695	**0.0002**	0.8250	**1.4488E-06**
8.	0.5941	0.3632	0.1161	**0.0093**
9.	0.6455	0.2962	0.8367	**0.0404**
10.	0.4421	**0.0188**	0.0620	**0.0017**
11.	0.0968	0.2025	0.7901	0.0867

The obtained results (Table 1) have indicated that the course of both isotherms was typical and have allowed to classify them as type II in the Brunauer's classification. The first part of the sigmoidal isotherm corresponds to the low values of water activity present in the atmosphere. This area is consistent with the coverage of energetically different hydrophilic groups on the surface of the particles by water molecules. Covering all available hydrophilic groups by water molecules is equivalent to formation of a monolayer. This value is specific to each product and depends on its chemical composition and physical structure. The second area on the sorption isotherm corresponds to the average values of water activity present in the environment, which is in equilibrium with the tested product. This part of the isotherm describes the state in which a multilayer is formed, and this is associated with the appearance of water-water interactions. These bonds are weaker than the water-matrix, which are characteristic of the first zone of the sorption isotherm. The third area of the sorption isotherm, which corresponds to the high values of water activity present in the atmosphere, starts the phenomenon of capillary condensation in the microcapillaries, which are filled first. Then the mesocapillaries and macrocapillaries fill up.

The course of the sorption process under the influence of the increasing saturation of the air with water vapor was expressed in the theory of multilayer adsorption [4] and capillary condensation [40]. Minor coverage of the adsorbent surface with water molecules (the first area on the sorption isotherm) causes water-matrix interactions, which determine the energy state of the adsorbent surface. However, each adsorbed water molecule changes the sorption conditions. After coverage of all available, although usually energetically different, active centers, the intermolecular forces become homogeneous, represented mainly by water-water interactions (the second sorption area on the sorption isotherm). This type of interaction at an appropriate high water content in the environment leads to the filling of some capillaries. This phenomenon is known as capillary condensation, which corresponds to the third area on the sorption isotherm.

Lewicki et al. [22] claimed that the existence of the connection between the rate of sorption and the stage of the process described by particular areas on the sorption isotherm entitles to determine such parameters, based on sorption isotherms, as: monolayer capacity and water content required for initiation of capillary condensation in the tested material. For the analysis of the sorption phenomenon, various mathematical models of sorption isotherms has been used, through exploring empirical data. The BET model deserves attention. This model is one of the most widely used theoretical models. It is based on the assumptions defined by Langmuir in the multimolecular idea of sorption. The BET model makes the transformation of empirical data and the determination of the monolayer capacity (vm), and the energy constant (C) possible. The BET equation is the most commonly used model to study surface phenomena occurring in food. It is used to interpret multilayer sorption isotherms, especially those of types II and III. It has been found to be an effective method of estimating the amount of water associated with the polar molecules of dehydrated food. This model assumes that the sigmoidal shape of the isotherm results from multilayer adsorption. Therefore, this approach acknowledges that each adsorbed molecule becomes the adsorption site for the next molecule of adsorbate. The forces involved in the formation of successive layers are analogous to the forces causing the condensation of vapor into a liquid. On the other hand, it should be emphasized that the BET equation, regardless of the chosen method for identifying its parameters (analytical or numerical), describes well the course of the sorption phenomenon only in a limited range of water activity (0.05 ÷ 0.5) [33].

Taking into account the limitations of the BET model, its parameters were estimated in the range indicated as properly corresponding to empirical data. The values of the sums of squared deviations and the error values with which they were determined, demonstrate that the BET model describes the process of water vapor adsorption on the surface of soybean meal properly (Table 3).

Table 3. Parameters of the BET model of isotherms of soybean meal determined at 20°C under the control conditions and under the influence of a homogeneous, static magnetic field with an induction of 10 mT

Parameter	Control conditions		Conditions with the influence of a magnetic field	
	Value	Standard error	Value	Standard error
v_m - monolayer [g $H_2O \cdot 100^{-1}$ d.m.]	5.5892	2.3716	7.0856	3.1486
a_w - water activity corresponding to the monolayer [-]	0.0573		0.1125	
C - energy constant [-]	1.1670	0.3545	0.9596	0.3122
SS - sums of squared deviations	5.7904	1.3893	6.6157	1.4850

The water content corresponding to the coverage of the surface of the meal's particles with a monolayer of water is the minimum, and at the same time, the optimal water content. This water content determines the durability of the dry product, because it signifies low water activity. This water does not freeze at -40°C, it cannot act as a solvent, it has no plasticizing properties, it does not cause hydrolytic reactions, but at the same time, it protects against oxidative reactions. In practice, the knowledge of this parameter is used to determine the end point of the drying process. It is worth mentioning, that this action is intended to optimize the costs of technological processes, and it is also important in the storage and transport of food. According to Karel [19], most food products have a monomolecular capacity from 4 to 11 kg per 100 kg of dry substance. The monolayer values determined with the use of the BET model were in the range of 5.59 ÷ 7.09 g H_2O per 100 g of dry matter. The monolayer volume (v_m) estimated using the BET model indicates the availability of polar sites for water vapor. The volume of monolayer is determined by the components that are donors of hydrophilic groups and by their physical state conditioned by, for example, the degree of comminution [27]. The amount of water in the product greater than the capacity of the monomolecular layer leads to the reaching of a critical water content, the exceeding of which causes various undesirable changes in the quality of the product. The differentiation of the monolayer values of the tested samples of soybean meal may indicate the different state of water molecules as a result of the influence of the magnetic field. At the same time, taking into consideration everything that has been discovered about the volume of the monolayer so far, it can be stated that soybean meal under the influence of the magnetic field is less sensitive to higher concentration of water vapor in the environment. A higher value of the monolayer indicates that the meal, going to reach equilibrium with the environment, can absorb more water, which will be strongly bound to its matrix. Therefore, changes of a hydrolytic nature will not be intensified, while changes of an oxidative nature should be limited. This assumption has been made on the basis of previous findings, which indicated that hydrolytic changes require adequately high water activity. Moreover, the higher water content of relatively low water activity, should limit the access of oxygen to the larger surface of the soybean meal particles. What is worth mentioning is the fact, that this should restrain the contact of oxygen with the lipid fraction, reducing the risk associated with their oxidation.

The second parameter of the BET model is the energy constant. The energy constant C reflects the difference between the monolayer desorption enthalpy and the enthalpy of vaporization of the liquid adsorbent. Its values in both cases were very low, what indicates the physical nature of the researched phenomenon. Therefore, it can be concluded that the influence of the magnetic field does not change the nature of the water vapor sorption process, which is still fully reversible. This statement is an additional argument in undertaking further research on the role of the magnetic field in stabilizing the quality of dry bulk cargo during transport, especially maritime.

6 CONCLUSIONS

Maintaining low water content, and consequently low water activity, is the primary factor in preserving the quality of a dry bulk cargo, such as soybean meal. Furthermore, the low water content also ensures microbiological safety. On the other hand, the low water content facilitates the dusting of the cargo and the increase of the risk of explosion during cargo handling operations.

The elementary method of stabilizing the quality of soybean meal is its deep dehydration, although it should be emphasized that this method has reached the limits of its usefulness. This is because of the challenge to maintain the low water content, which is problematic. Therefore, it is reasonable to search for new, also unconventional, methods allowing the stabilization of water content and, especially, water activity.

Currently, the methods facilitating the optimization of procedures related to preparation and handling of bulk cargo for transport and storage are being searched. In reference to that, the obtained results indicate that soybean meal, which is a highly hygroscopic cargo, is also sensitive to water, in the form of vapor. Moreover, it was found that the influence of a homogeneous, static magnetic field is a factor that differentiates the water content and water activity in the soybean meal. The exploration of empirical results with the use of BET model has indicated that the influence of the magnetic field is a factor that differentiates also the sorption properties of soybean meal. Under the impact of magnetic field, the volume of the monolayer is greater, which makes the soybean meal less sensitive to the surrounding water vapor. At the same time, the energy connected with the sorption phenomenon under the influence of the magnetic field does not change. Therefore, the magnetic field does not change the nature of the sorption process. Consequently, there are indications that the presence of a strong magnetic field may determine the stability of the cargo during long-term transport or storage.

REFERENCES

1. Ambashta, R.D., Sillanpää, M.: Water purification using magnetic assistance: A review. Journal of Hazardous Materials. 180, 1, 38–49 (2010). https://doi.org/10.1016/j.jhazmat.2010.04.105.
2. Baker, J.S., Judd, S.J.: Magnetic amelioration of scale formation. Water Research. 30, 2, 247–260 (1996). https://doi.org/10.1016/0043-1354(95)00184-0.
3. Blokus, A., Dziula, P.: Safety Analysis of Interdependent Critical Infrastructure Networks. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation. 13, 4, 781–787 (2019). https://doi.org/10.12716/1001.13.04.10.
4. Brunauer, S., Emmett, P.H., Teller, E.: Adsorption of Gases in Multimolecular Layers. J. Am. Chem. Soc. 60, 2, 309–319 (1938). https://doi.org/10.1021/ja01269a023.
5. Czerniawski, B., Michniewicz, J.: Opakowania żywności. Agro Food Technology, Czeladź (1998).
6. Denicoff, M.R., Prater, M.E., Bahizi, P.: Soybean Transportation Profile. U.S. Department of Agriculture, Agricultural Marketing Service. (2014). https://doi.org/10.9752/TS203.10-2014.
7. Drzewieniecka, B., Drzewieniecki, J., Blatnický, M.: The Influence of External Factors on Hazards in the Transport Processes of Soybean Meal. New Trends in Production Engineering. 1, 1, 301–307 (2018). https://doi.org/10.2478/ntpe-2018-0037.
8. Dutkiewicz, E.T.: Fizykochemia powierzchni. WNT, Warszawa (1998).
9. Fathi, A., Mohamed, T., Claude, G., Maurin, G., Mohamed, B.A.: Effect of a magnetic water treatment on homogeneous and heterogeneous precipitation of calcium carbonate. Water Research. 40, 10, 1941–1950 (2006). https://doi.org/10.1016/j.watres.2006.03.013.
10. Fey, D.P., Greszkiewicz, M., Otremba, Z., Andrulewicz, E.: Effect of static magnetic field on the hatching success, growth, mortality, and yolk-sac absorption of larval Northern pike Esox lucius. Science of The Total Environment. 647, 1239–1244 (2019). https://doi.org/10.1016/j.scitotenv.2018.07.427.
11. Figura, L., Teixeira, A.A.: Food Physics: Physical Properties - Measurement and Applications. Springer-Verlag, Berlin Heidelberg (2007). https://doi.org/10.1007/978-3-540-34194-9.
12. Gondek, E., Lewicki, P.P.: Kinetics of Water Vapour Sorption by Selected Ingredients of Muesli-type Mixtures. Polish Journal of Food and Nutrition Sciences. 57, 3A, 23–26 (2007).
13. Hartman, G.L., West, E.D., Herman, T.K.: Crops that feed the World 2. Soybean—worldwide production, use, and constraints caused by pathogens and pests. Food Security. 3, 1, 5–17 (2011). https://doi.org/10.1007/s12571-010-0108-x.
14. Helpman, E.: The Mystery of Economic Growth. Belknap Press: An Imprint of Harvard University Press (2010).
15. Helpman, E., Itskhoki, O., Redding, S.: Inequality and Unemployment in a Global Economy. Econometrica. 78, 4, 1239–1283 (2010). https://doi.org/10.3982/ECTA8640.
16. Higashitani, K.: Effects of magnetic field on stability of non-magnetic colloidal particles. In: Proceedings of the 2nd International Meeting on Anti-Scale Magnetic Treatment. , Cranfield University, UK (1996).
17. Huespe, V.J., Belardinelli, R.E., Pereyra, V.D., Manzi, S.J.: Comparison between different adsorption–desorption kinetics schemes in two dimensional lattice gas. Physica A: Statistical Mechanics and its Applications. 488, 162–176 (2017). https://doi.org/10.1016/j.physa.2017.06.028.
18. Ji, Y., Wang, Y., Sun, J., Yan, T., Li, J., Zhao, T., Yin, X., Sun, C.: Enhancement of biological treatment of wastewater by magnetic field. Bioresource Technology. 101, 22, 8535–8540 (2010). https://doi.org/10.1016/j.biortech.2010.05.094.
19. Karel, M., Lund, D.B.: Water Activity and Food Preservation. In: Karel, M. and Lund, D.B. (eds.) Physical Principles of Food Preservation. p. 53 CRC Press, New York (2003).
20. Kędzierska-Matysek, M., Matwijczuk, A., Florek, M., Kornarzyński, K., Matwijczuk, A., Wolanciuk, A., Barłowska, J., Gładyszewska, B.: Wpływ pola magnetycznego na zawartość 5-hydroksymetylofurfuralu, aktywność diastazy oraz zmiany w widmach ATR-FTIR w świeżych miodach gryczanych. Przemysł Chemiczny. 97, 3, 381–386 (2018). https://doi.org/10.15199/62.2018.3.8.
21. Lehuger, S., Gabrielle, B., Gagnaire, N.: Environmental impact of the substitution of imported soybean meal with locally-produced rapeseed meal in dairy cow feed. Journal of Cleaner Production. 17, 6, 616–624 (2009). https://doi.org/10.1016/j.jclepro.2008.10.005.
22. Lewicki, P.P., Lenart, A., Placzek, A., Skrzeszewski, S.: Kinetyka sorpcji pary wodnej przez wybrane produkty spożywcze. Przemysl spożywczy. 41, 11, 428–432 (1977).
23. Lusser, M., Parisi, C., Plan, D., Rodriguez Cerezo, E.: New plant breeding techniques : state-of-the-art and prospects. Publications Office, European Commission. Joint Research Centre. Institute for Prospective Technological Studies (2011).
24. McFarlane, I., O'Connor, E.A.: World Soybean Trade: Growth and Sustainability. Modern Economy. 5, 5, 580–588 (2014). https://doi.org/10.4236/me.2014.55054.
25. Mittal, A.: The 2008 Food Price Crisis: Rethinking Food Security Policies. United nations (2009).
26. Mukherjee, R., Chakraborty, R., Dutta, A.: Soaking of soybean meal: evaluation of physicochemical properties and kinetic studies. Journal of Food Measurement and Characterization. 13, 1, 390–403 (2019). https://doi.org/10.1007/s11694-018-9954-6.
27. Ocieczek, A.: Comparison of the sorption properties of milk powder with lactose and with-out lactose. Acta Agrophysica. 21, 4, 457–468 (2014).
28. Ocieczek, A., Otremba, Z.: Effect of a magnetic field on water desorption from the surface of potato starch. Acta Agrophysica. 26, 3, 43–55 (2019). https://doi.org/10.31545/aagr/114987.
29. Ocieczek, A., Otremba, Z.: The Influence of Magnetic Field on the Course of Surface Phenomena in the Food Quality Development. Presented at the X Międzynarodowa Konferencja Naukowa, Rola

towaroznawstwa w zarządzaniu jakością w warunkach gospodarki opartej na wiedzy , Gdynia (2020).
30. Ocieczek, A., Otremba, Z.: Water Vapor Sorption on the Surface of Selected Organic Samples in an Artificial Static Magnetic Field of 10 mT. International Journal of Technology. 11, 3, 291–319 (2020). https://doi.org/10.14716/ijtech.v11i3.3831.
31. Pałacha, Z., Sitkiewicz, I.: Właściwości fizyczne żywności - Zbigniew Pałacha, Iwona Sitkiewicz WNT Wydawnictwa Naukowo-Techniczne - Podręczniki | Gandalf.com.pl. WNT, Warszawa (2010).
32. Rahman, M.S.: Food Stability Beyond Water Activity and Glass Transtion: Macro-Micro Region Concept in the State Diagram. null. 12, 4, 726–740 (2009). https://doi.org/10.1080/10942910802628107.
33. Rizvi, S.S.H.: Thermodynamic Properties of Foods in Dehydration. In: Rao, M.A. (ed.) Engineering Properties of Foods. p. 88 CRC Press (2005). https://doi.org/10.1201/9781420028805-11.
34. Sandle, T.: The Importance of Water Activity for Risk Assessing Pharmaceutical Products. Journal of Pharmaceutical Microbiology. 2, 1, (2016).
35. Schmidhuber, J., Tubiello, F.N.: Global food security under climate change. Proceedings of the National Academy of Sciences. 104, 50, 19703–19708 (2007). https://doi.org/10.1073/pnas.0701976104.
36. Wang, Y., Pugh, R.J., Forssberg, E.: The influence of interparticle surface forces on the coagulation of weakly magnetic mineral ultrafines in a magnetic field. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 90, 2, 117–133 (1994). https://doi.org/10.1016/0927-7757(94)02908-3.
37. Zawadzki, M.: Transport of Frozen Products as a Source of Environmental and Consumer Risks. Scientific Journal of Gdynia Maritime University. 116, 88–99 (2020). https://doi.org/10.26408/116.05.
38. Zhang, H., Zhao, Z., Xu, X., Li, L.: Study on industrial wastewater treatment using superconducting magnetic separation. Cryogenics. 51, 6, 225–228 (2011). https://doi.org/10.1016/j.cryogenics.2010.07.002.
39. Zięba, M., Ocieczek, A., Czerwonka, D.: Application of Selected Methods for Evaluating the Quality of Powdery Products as Stability Indicators of Cosmetics in Powder form on the Example of Dry Shampoos. Towaroznawcze Problemy Jakości. 2, 126–135 (2019). https://doi.org/10.19202/j.cs.2019.02.12.
40. Zsigmondy, R.: Structure of gelatinous silicic acid. Theory of dehydration. Zeitschrift für anorganische und allgemeine Chemie. 71, 1, 356–377 (1911).