Keywords: sea cargo, brown rice, sorption isotherm, BET model, chlorides, Mohr method

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THE DIVERSITY OF THE SORPTION PROPERTIES OF RICE DURING MARITIME TRANSPORT AS AN ELEMENT OF RISK ASSESSMENT IN THE LOGISTICS PROCESS

Summary. In this study, a comparative assessment of selected parameters determining the quality of rice transported by sea has been carried out. The aims of this process were to point out the differences between two types of rice tested immediately after their maritime transport and to compare these with a reference rice available in retail. Undoubtedly, the scientific achievement of the article is the demonstration of the possibility that the identification and estimation of the risk of lowering or total loss of quality (usability) of cargo are connected to its transport and related to the initial conditions. The analysis of the obtained results showed the existence of a sensitive dependence of the final state of the charge quality on the initial conditions, which is in line with the theory of deterministic chaos expressed as the butterfly effect.

1. INTRODUCTION

Trade in Asian goods has been ongoing for hundreds of years. In the 16th century, the trade in Asian spices became so profitable that special trade companies were launched for this purpose. For centuries, these goods had been transported using land transport. However, when the Portuguese discovered the sea route via the Cape of Good Hope, new, very propitious prospects for the development of trade appeared [12]. The trade included not only spices but also other bulk cargo, such as cereals. Although the duration of bulk cargo transport has significantly shortened (from 14 months in 1599 to approx. 40-70 days in 2022) and its technical security has improved, the risk of the deterioration or damage of goods during maritime transport still exists [8, 15]. Due to this fact, the insurance business has been launched and developed. This also involved the most complicated marine insurance, which, early on, was nothing more than a kind of gamble. This is because, at that time, there were no theoretical grounds for assessing the insured risk. This is the development of science that enabled the creation of the basis for rational insurance activity. The milestones in this area comprise probability theory developed by Blaise Pascal and Pierre de Fermat, as well as John Graunt and Edmund Halley [14], the concept of certainty defined by Jacob Bernoulli, the conception of normal distribution proposed by Abraham de Moivre, the utility theory created by Daniel Bernoulli, and the inference method described by Thomas Bayes [3]. The modern insurance system has undoubtedly developed in connection with merchant activity but also owing to the achievements of mathematicians [8].

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In relation to mathematics achievements, as well as to historical knowledge, it should be recognized that events that will happen in the future may be located in the domain of uncertainty, as well as in the domain of risk. However, it should be emphasized that the uncertainty (unmeasurable) is fundamentally different from the risk, which can be estimated (measurable). Accordingly, science, which has two main areas of interest—explaining the occurring changes and formulating simple laws which enable predictions of these changes in the future—seems to be a key factor in the development of risk estimation. Therefore, it is considered reasonable to conduct research on the recognition and characterization of the nature of phenomena, which enable improvements in the risk assessment of, for example, the deterioration in goods quality under transport conditions. Thus, we postulate the necessity of taking advantage of knowledge from the natural and technical sciences in the field of marine insurance. The implementation of this assumption in practice will contribute to the efficient identification of the parties involved in the logistics process who are responsible for goods/cargo transport damage throughout the logistics chain [17]. This approach, according to the authors of this article, will increase the responsibility and care of the parties involved in the logistics process for their actions. In reference to the statement that the processes described in Darwin's theory of evolution occur in economics, we postulate that these processes also function in management. It is worth mentioning that management processes, including the management of logistics, take place in a particular social, natural, and technical environment that changes owing to its different dynamics. These changes should induce modifications in the parameters of managerial actions. At the same time, the evolutional nature of management should be associated not only with an increase in the human population and an increase in capital but also (and especially) with the development of science and the accumulation of its achievements. Many problems, particularly the Malthusian trap, can be avoided by basing efficient management on each of the main driving forces of civilization's progress, which are the growing power of money, the development of science, and the spread of the rule of law [8].

The current research takes the above into consideration. The aim was to compare the parameters describing the diversity of hygroscopicity of rice as an inherent feature critical to its quality and safety. Rice is a bulk cargo that is transported by sea. Therefore, it was assumed that a full description of the hygroscopic properties of rice and the law of large numbers enable predictions of particular incidents and, thus, control of the risk connected with their occurrence. This is because there is no doubt that in similar conditions, the occurrence (or non-occurrence) of a quality change in the future is as probable as it was in the past and, therefore, in the conditions of our experiment. Accordingly, this, together with documented data about the course of changes in environmental parameters during maritime transport, will become an important element enabling the indication of the root causes of a particular level of quality and safety of cargo after the transport process. Thus, instruments for assessing the risk of deterioration in quality and safety of hygroscopic cargo during maritime transport will be developed. In addition, it will be possible to identify weak spots in the logistics chain that generate transport losses. As a consequence, it is expected that the increase in insurance costs will be limited, the functioning of the logistics chain will be improved, and, most of all, food waste connected with its turnover will be reduced. These consequences are part of the concept of sustainable development.

The object of this research is *Oryza sativa L.*, which is the most commonly cultivated rice type. This type of grain is the basic raw material for food production for almost 4 billion people worldwide, and it is the second most cultivated grain after maize. About 80% of the world's rice production is used as human food, and only 20% is used as animal feed [40].

Over the last three decades, rice production has increased by 130% [21]. The world's rice production in 2021 was 519.3 million tonnes [11]. The largest producers of rice in the world are China (206.3 million tonnes per year), India (166.5 million tonnes/year), and Indonesia (73.9 million tonnes/year) [10]. Poland, like other European countries, due to its geographical location, does not produce rice, although it imports it. The value of rice imports to Poland in 2019 was $274 million. Poland imports rice mainly from Italy, Germany, and Myanmar [29]. According to the FAO [10], in the next few years, the consumption of rice in the world will exceed its production, which will lead to the necessity of using the world's rice reserves. The volume of trade in rice is constantly growing, and rice's value is constantly increasing. Therefore, rice should be considered a strategic raw material, and thus, research on changes in its quality, losses related to its turnover, and their effects on the environment should be considered socially significant.

The quality of rice is the result of many features. There is no doubt that one of rice's main characteristics, which should be considered to be an advantage, is its nutritional value. Rice is a rich source of starch, protein, minerals, vitamins, and dietary fiber [9]. Due to the structure-forming properties of rice, it is used increasingly often in gastronomic technology, especially in the production of rice flour, rice pasta, rice flakes, rice drinks, rice wafers, rice paper, and special-purpose products consumed by people with a gluten intolerance [4]. Moreover, rice is easy to prepare during thermal processing, and it is sensory attractive; for these reasons, it is frequently chosen by consumers all over the world [41].

Post-harvest processing stages, such as drying and storage, have a significant influence on the quality of rice. Rice acquires its characteristic taste, aroma, and texture during its storage. These properties are created as a result of the activity of many enzymes, such as peroxidases, catalase, amylase, proteases, lipase, and lipoxidases. The activity of these enzymes changes the structure of the rice hull and its chemical composition [40].

The changes in the water content during the drying and storage process are also important to the quality of the rice. Providing the appropriate water level in the rice matrix enables its long-term storage. Rice is a material with strong sorption properties. It is worth mentioning that the hygroscopic properties that reflect its interaction with water molecules are especially significant. Therefore, hygroscopic properties play an extremely important role in rice processing, storage, and transport [32].

There is no doubt that water sorption isotherms are valuable tools for determining and comparing the hygroscopic properties of rice. The identification of their graph allows one to determine the water content in the monomolecular layer considered optimal for the material's storage stability. Moreover, sorption isotherms can be used in the organization of the drying process and storage process, as well as in the selection of packaging and the method and conditions of transport [24, 32]. The graph of the sorption curve enables one to determine the conditions necessary to maintain the microbiological safety of the product [36, 20]. Their identification is also a starting point for in-depth analyses of changes in hygroscopic properties caused by modifications of environmental conditions. For this purpose, it is necessary to use the theory of surface thermodynamics (e.g., the Polanyi adsorption potential theory). The reliance on the achievements of natural and technical sciences enables the exploration of the data contained in sorption isotherms without the need to conduct empirical research each time [6]. Thus, the idea of scientific progress is implemented through an interdisciplinary approach to the identified practical problem.

The aim of this study was to create a basis for research on the variability of rice quality and safety determined by transport conditions. The main stage of this work involves the comparison of selected hygroscopic parameters of three rice samples. Two of these rice samples were obtained immediately after the process of maritime transport. The third sample, considered to be the reference sample, was a product available on the retail market.

2. MATERIALS AND METHODS

The research materials consisted of rice samples obtained from the cargo ship docking at the grain terminal in Gdynia, Poland. The samples were long-grain brown rice (R_1) and parboiled brown rice (R_2). Long-grain brown rice available on the retail market, which was the reference sample, was also assessed (R_0) in order to compare the quality parameters of the tested samples.

The test samples were taken from the ship's hold at random according to the sampling procedure. The quantity of the sample used for testing was not less than 2 kg. The test material was stored in polyethylene bags.

Rice, as a natural cereal product, is characterized by considerable variability resulting from both heterogeneity in its physical structure and the chemical composition of caryopsis. This feature determines its sorption properties. Therefore, the water content and water activity were first determined for each of the tested rice samples, and then the obtained results were expressed as an arithmetic mean and standard deviation calculated on the basis of three parallel designations.

The initial water content in the tested products was identified by the gravimetric method after drying to a constant mass at a temperature of 373-378 K (100-105°C) under normal pressure [18].

Water activity was identified via the dew point method using the AquaLab 4TE meter (version AS4 2,14.0 2017 Decagon Devices, Inc.) with ± 0.0003 accuracy at 293 K (20 °C) ± 2.5 K.

Further, sorption isotherms were determined as the resultant functions of physical and chemical properties that determine the chemical affinity to water in order to obtain reliable results so that the hygroscopic properties of the investigated rice samples could be compared. Water sorption isotherms were identified by the standard static desiccator method using saturated solutions of different substances [28]. The tests were carried out in an environment with a water activity of 0.07 to 0.98 and a constant temperature of 293.15 K (20 °C). Rice samples were placed at about 1 g ± 0.01 mg in weighing dishes with a diameter of nearly 40 mm in desiccators to establish the equilibrium state of the system, which was manifested by an insignificant change in the mass of the tested samples over time. Thymol was placed in desiccators with a water activity above 0.7 in order to eliminate microflora.

The equilibrium water content was estimated on the basis of the identification of the initial water content in the product and its change related to the migration between the sample and its environment until reaching the state of dynamic equilibrium. At the same time, the water activity was measured. Sorption isotherms, which describe the typical for each dry substance correlation between the water content and water activity in the sample, were determined on the basis of these data. Graphical models of isotherms were compared using Student's t-test to determine the differences between the means of bond pairs. Differences at the level of $p \leq 0.05$ were considered to be statistically significant.

Subsequently, in reference to empirical data about water activity in the range from 0.07 to 0.44, the parameters of the linear function in the $y=ax+b$ form were determined. The method of least squares was used. The objective function was the minimization of the sum of squared deviations (SSD):

$$SSD = \sum(v_e - v_0)^2 \tag{1}$$

where:
v_e - experimental equilibrium water content (g H_2O/100 g d.m.); v_0 - calculated equilibrium water content (g H_2O/100 g d.m.) [27].

Moreover, methods were used to fit a linear function to empirical data, such as the coefficient of determination (R^2), correlation coefficient (R), residual standard deviation – standard error (SE), and coefficient of convergence (φ^2).

At the same time, confidence intervals for functions with parameters a and b generated in the process of analytical procedures were presented. This element of assessment of the predictive capacity of the model was used due to the widespread over-reliance on calibration, which leads to diminishing the role of confidence intervals in the range of which the assessments and estimations appear to be reasonable. The aim was to eliminate the tendency to equate the "most favorable" solution with the "most probable" solution.

In the next step, according to the procedure described by Paderewski [30], the parameters a and b of the linear function were used to calculate the parameters of the theoretical sorption model of Brunauer, Emmett, and Teller (BET) [5] in the form of

$$v = \frac{v_m \cdot c \cdot a_w}{(1-a_w)\cdot[1+(c-1)\cdot a_w]} \tag{2}$$

where:
a_w - water activity (-); v - equilibrium water content (g H_2O/100 g d.m.); v_m - water content in the monolayer (g H_2O/100 g d.m.); c - energy constant, which is exponentially related to the difference between the heat of adsorption of the first and subsequent layers, assumed to be constant and equal to the heat of condensation [30, 2].

For this purpose, the BET equation (2) was subjected to transformation, according to which

$$a = \frac{1}{v_m \cdot c} \tag{3}$$

whereas

$$b = \frac{c-1}{v_m \cdot c} \tag{4}$$

Hence, it follows that the parameters of the BET equation expressed using the coefficients of the linear function of the form $y=ax+b$, estimated by the least squares method, are

$$c = \frac{b}{a} + 1 \tag{5}$$

whereas

$$v_m = \frac{1}{a \cdot c} \tag{6}$$

Thus, if the parameters a and b of the linear function are known, the value of the energy constant c can be determined. Then, on the basis of the parameter a and the energy constant c, the value describing the water content in the monolayer v_m can be determined.

The identification of the parameters of the BET model (c and v_m) made it possible to estimate the water content and water activity in the investigated rice samples, which will help to maintain their high quality and safety. Based on these parameters, it was possible to indicate the level of relative air humidity, which has been in the equilibrium state with the individual rice samples. Parameters determined in this way are useful for preparing the cargo hold and monitoring its condition during maritime transport in order to stabilize the quality and safety of the cargo, which is rice.

The fitting of empirical data to the course of the BET equation in the range of $0.07 < a_w < 0.44$ was determined in accordance with the SSD and root mean square error (RMSE), expressed in %, which was calculated on the basis of the following equation:

$$RMSE = \sqrt{\frac{\sum(\frac{v_e - v_0}{v_e})^2}{N}} \cdot 100\% \tag{7}$$

where

N - number of data points [19].

Moreover, on the basis of the water setting surface, which is the surface occupied by a water molecule, and the volume of water vapor adsorbed at a temperature lower than the boiling point, the specific surface area of the adsorbent was calculated from the following equation:

$$a_{sp} = \omega \frac{v_m}{M} N \tag{8}$$

where:

a_{sp} - specific surface area of sorption (m^2/g); N - Avogadro constant ($6.023 \cdot 10^{23}$ molecules/mol); M - molecular mass of water (18 g/mol); ω - water setting surface ($1.05 \cdot 10^{-19}$ m^2/molecule) [30].

Apart from the research on sorption properties, chlorides were determined in the tested samples using the Mohr method [38]. Determining the concentration of chlorides in the tested samples and comparing it with the average values specific to this type of product may serve as an indicator of the contact of the tested sample with seawater. NaCl content was calculated in mg/g according to the following formula:

$$x = \frac{V \cdot M \cdot 0.05845}{m} \cdot 100 \tag{9}$$

where:

V - volume of 0.1M $AgNO_3$ solution (ml); M - molarity of the $AgNO_3$ solution; m - mass of test product in titration solution (g); 0.05845 - the number of grams of table salt coherent with 1 ml of 0.1 M $AgNO_3$ solution [37].

3. RESULTS AND DISCUSSION

The sorption properties of cereals, including rice, are the result of many elements affecting the affinity of the grain surface to water vapor and other gases. The most frequently mentioned elements of the environment that have a significant influence on the quality and safety of rice during its storage are water activity and content [20]. These elements determine the direction and the dynamics of the processes taking place at that time [23].

Table 1 presents the average initial water content and water activity in the tested rice, which were determined from three simultaneously checked samples. It has been recognized that the highest initial water content and water activity are associated with long-grain brown rice (R_1), followed by parboiled brown rice (R_2) and the reference rice (R_0). Pałacha and Sas [32] obtained similar values for parboiled brown rice, although their values obtained for long-grain brown rice were significantly lower. Thus, it was assumed that the higher water content in the samples of rice collected directly from the ship's hold was a consequence of the impact of environmental conditions on the cargo during its transport.

Table 1

Initial water content and activity of the tested samples of rice

Product	Initial water content [g H_2O/100 g d.m.]	Standard deviation [g H_2O/100 g d.m.]	Initial water activity [-]	Standard deviation [-]
R_0	9.4250	± 0.1467	0.5542	± 0.2831
R_1	11.1910	± 0.1930	0.6651	± 0.4208
R_2	9.9715	± 0.1119	0.6458	± 0.4385

The water activity determined simultaneously in samples R_1 and R_2 was significantly higher in comparison to the water activity in the reference sample. At the same time, it is important to emphasize that the value of water activity in samples taken from the ship's holds was so high that it posed a threat to microbiological safety [20] and undermined their storage stability [36].

The technological processes specific to the production of rice do not include activities that could increase the water content and, consequently, water activity. Therefore, it could be presumed that the tested rice samples had been exposed to inappropriate conditions during maritime transport or had undergone contact with seawater. Clarification of this issue required an additional determination. Thus, the determination of chloride content was conducted. Water content has the greatest influence on water activity; however, contact with water in the form of vapor does not lead to an increase in sodium chloride content, which exists in cases of contact with seawater in the form of liquid.

The chloride content was determined in order to identify the reason for the increased value of water activity in the investigated rice samples. The highest concentration was recorded in sample R_1 (1.5406 ± 0.0112 mg/g), followed by sample R_0 (1.1560 ± 0.0201 mg/g) and sample R_2 (1.0953 ± 0.0230 mg/g). The comparison of the obtained results suggests that the increased water activity in sample R_1 was the consequence of its contact with seawater, which is a source of NaCl, and, thus, could lead to a higher concentration of chloride in the tested sample. On the other hand, there are no indications that product R_2 has had contact with seawater. However, there are serious indications that the increased water activity must have been related to the influence of water vapor in the environment of the cargo during transport.

Sorption isotherms are undoubtedly the source of much important information about the water present in a material [25, 26]. This characteristic curve for each product can be expressed graphically.

Figure 1 shows the graph of water sorption isotherms for the tested rice. Points marked on isotherms are average values, and coefficients of variation range from 0.05% to 6.9% for reference rice, from 0.18% to 6.64% for long-grain brown rice, and from 0.11% to 7.35% for parboiled brown rice. The greater variability of the sorption isotherms parameters noticed in the case of rice samples collected from the ship's holds indicates a more heterogeneous nature of this material, determined by the impact of environmental conditions during transport. The graph of water sorption isotherms (Fig. 1) of all tested rice samples indicates that it is a highly hygroscopic material capable of absorbing significant amounts of water. The obtained curves, regardless of the type of rice, were characterized by a typical sigmoidal shape, specific for type II isotherms, in the classification of Brunauer and others [5]. Type II isotherms are characteristic of starch and protein products. This shape of sorption isotherm indicates that the water sorption process took place in three stages.

In the first stage, the water molecules occupied all free hydrophilic groups. The first inflection point on the sorption curve corresponds to the end of the filling of the monomolecular layer. The water present in the rice grains in this amount is the most strongly bound to the material, and thus, it does not constitute an environment necessary for the process of changes with a hydrolytic nature [34]. The volume of the monolayer—and, thus, the amount of water that fills it—depends on the proportion of hydrophilic polymers, such as proteins and polysaccharides, in the matrix of the grains. When this water content is exceeded, which most often occurs as a result of the storage of grain masses in a damp room or as a result of their flooding (e.g., during maritime transport), it leads to the initiation of the multilayer absorption phenomenon [24].

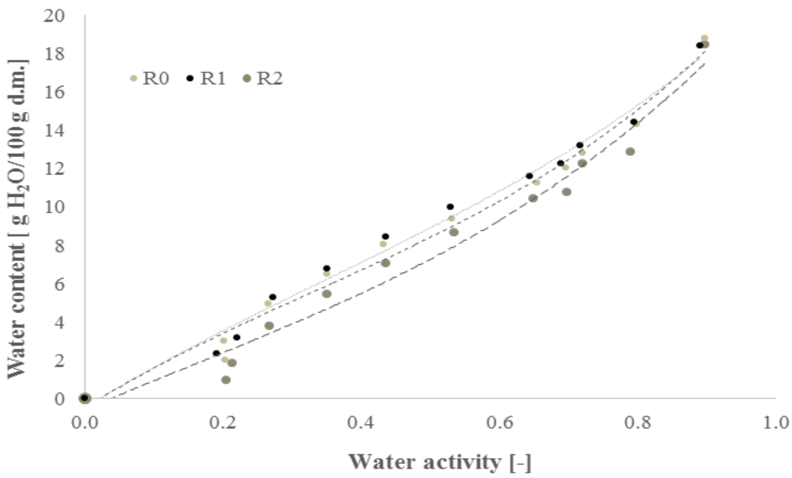

Fig. 1. Sorption isotherms of the water vapor of tested samples of rice

The second stage reflects the formation of a multilayer by the water molecules on hydrophilic groups. The presence of water in an amount that enables the formation of a multilayer causes the mechanical properties of the grain to change and the dynamics of chemical and biochemical reactions to increase significantly. The grain begins to breathe intensively, which leads to the release and accumulation of metabolic water and thermal energy. The coexistence of these two factors (heat and water), considered critical for the safety and quality of grain masses, leads to a rapid deterioration in the quality of this cargo [1].

The third stage in the sorption process, called capillary condensation, is initiated by filling the fewest capillaries on the grain surface with water. This radically increases the dynamics of all biochemical and physiological processes typical of living organisms [13]. At the same time, it enables the multiplication of a wide spectrum of microorganisms and the production of toxins by them to occur [34, 36]. The adsorption of water by hygroscopic material, such as rice, in an amount causing capillary condensation makes this material useless for further storage [1].

The evaluation of the graph of sorption isotherms indicates that, in terms of hygroscopicity, the reference sample (R_0) is more similar to the R_1 sample taken from the ship's hold than to the R_2 sample (also taken from the ship's hold). This means that the parboiling process to which the rice (R_2) was subjected significantly differentiated the properties of long-grain brown rice. Moreover, the results of the statistical evaluation of the isotherms confirmed that the tested samples differed from the reference sample to a different extent in terms of hygroscopicity. The results of the Student's t-test for the matched pairs ($t_{0.05}$=2.228; $t_{R0/R1}$=3.6053; $t_{R0/R2}$=9.9292; $t_{R1/R2}$=9.1538) indicate that the isotherms of all examined rice samples manifest statistically significant differences in the graph in relation to each other.

The water vapor sorption isotherm of parboiled brown rice (R_2) was characterized by a significantly lower position in relation to both other samples. Therefore, this rice manifested a lower affinity for water than the other tested samples. At the same time, it should be emphasized that such a graph of the isotherm indicates the lower capacity of the dry matrix of this rice to bind the absorbed water [23]. If the water content is equal, R_2 rice manifests a higher value of water activity and, therefore, a higher susceptibility to the occurrence of reactions that lead to deterioration in quality and safety. The obtained graph of results clearly shows that parboiled brown rice (R_2) is a more demanding load in comparison to long-grain brown rice (R_1). A relatively low humidity must be maintained in the ships' holds to ensure the stability of their quality and safety; however, this may be a serious problem in the conditions of maritime transport [26]. If the joint transport of rice with different physicochemical properties is conducted, the dynamics of changes in the quality and even in the safety of such load may vary. The factor initiating this differentiation may be the absorption of water vapor, as well as contact with seawater. Another more advanced way of not only assessing but also comparing hygroscopicity based on specific parameters expressed in numbers is to present isotherms using parameters of mathematical models [25]. For this purpose, the parameters of three linear functions were determined and their goodness of fit was measured (Table 2).

Table 2

Parameters of linear functions describing tested rice samples together with their goodness of fit

Product	Parameters of the linear model and measures of their fit to empirical data						
	a	*b*	SSD	R^2	R	Se	φ^2
R_0	24.0879	-2.0794	1.1397	0.9535	0.9765	0.6164	0.0465
R_1	24.8392	-2.0823	0.6277	0.9749	0.9874	0.4574	0.0251
R_2	25.1444	-3.5760	0.9627	0.9617	0.9807	0.5665	0.0383

The comparison of the values of the parameters of the declared functions allows us to state that the tested material belongs to the same commodity/load group in terms of sorption properties. At the same time, differences were identified between each sample, indicating different susceptibilities to the influence of water. It is worth emphasizing that the R_2 sample was significantly different from the other two. The high value of the directional coefficient determined for the R_2 sample proves its high sensitivity to the presence of water vapor in the environment. If the increase in the relative humidity of the atmosphere is equal, the water content in the R_2 sample increases more dynamically than in the other two. R^2, R, Se, and φ^2 were estimated in order to assess the prognostic ability of the linear models used parameters, the analysis of which showed that the conducted empirical and analytical procedure (and, subsequently, the inference) were based on justified assessments and estimates. Thus, it has been confirmed that the conclusions based on the results of empirical research and the proposed analytical approach are focused on searching for the solution that is the most probable, not the most favorable. Therefore, it should be assumed that the selected linear model, as well as the BET model parameters determined on its basis, have high prognostic utility.

The BET equation was also applied to describe the isotherms of rice grain [32, 33]. The BET equation is a theoretical model that complements the interpretation of sorption isotherms. Therefore, it has been accepted as a general method for determining adsorbent surfaces from sorption data [24]. The choice of the basic BET model for the reviewed research was influenced by the fact that despite its confines, this model is still used to calculate the monolayer in various areas of physicochemical research, and thus, the obtained results can be compared [27]. In addition, this model is approved by the IUPAC [39]. The BET model, despite limitations resulting from its linear form, which favors the tendency to overestimate the predicted amount of vapor adsorbed by the sorbent at high pressure, is an effective tool for predicting the amount of bonded water in particular polar positions [1]. Therefore, it was used to describe the phenomenon in the range of water activity limited from 0.07 to 0.44. The parameters and the fitting of empirical data to the course of the BET equation expressed as SSD and RMSE are presented in Table 3.

The comparison of SSD indicated the existence of relatively large differences in the value of this parameter between the R_2 sample and R_0 and R_1 samples, for which these values were similar. Thus, it was found that the BET model used to describe the empirical data better fit the dataset describing the R_2 sample than the R_0 and R_1 samples. However, taking into account the limitations of the SSD index to assess the fit of the model to empirical data, the RMSE has also been estimated. In accordance with

Pałacha and Sas [32], it has been admitted that an RMSE lower than 10% indicates a good fitting of a model to empirical data in a particular range of water activity. Based on that, it has been established that the BET equation reflected the empirical data of all investigated rice samples very well. Thus, the generated parameters of the BET model can be considered to be reliable and comparable, and their interpretation has application value.

The first of the estimated parameters was the energy constant *c*, the values of which were related to individual rice samples and situated in a narrow range (4.39-4.64). The energy constant (*c*) in the case of physisorption is around 20 $kJ\cdot mol^{-1}$. On the other hand, in the case of chemisorption, it is much higher, and its typical values are about 200 $kJ\cdot mol^{-1}$. Hence, it was concluded that the studied process was a physical phenomenon, and the characteristic of physically adsorbed water molecules did not change significantly. Only the interaction of the surfaces can cause irrelevant deformations. Therefore, it can be concluded that the water molecules did not react with the molecules present on the surface of the dry rice matrix. Thus, the adsorbed water could be removed from the matrix relatively easily by supplying energy from the outside [2, 30]. However, the verification of the postulate concerning the nature of the observed phenomena should be additionally improved based on the results of spectroscopic tests. The second of the estimated parameters is the monomolecular layer v_m. The volume of the monolayer (v_m) characterizes the sorption capacity of the adsorbents and acts as an indicator of the availability of polar positions for water vapor [1]. If the concept of the monolayer is comprehended, it is also possible to analyze various aspects of the physical and chemical deterioration of dry food products [22].

Table 3

BET equation parameters of the tested samples of rice

Product	Parameters of the BET model					
	c [-]	v_m [g H_2O/100 g d.m.]	a_w [-]	SSD	RMSE [%]	a_{sp} [m^2/g d.m.]
R_0	4.5437	10.5841	0.5257	124.78	1.9928	371.86
R_1	4.3943	10.9286	0.5238	125.11	1.4948	383.97
R_2	4.6365	6.0313	0.3821	20.85	2.5741	211.90

The largest monolayer was identified in the sample of long-grain brown rice, and the smallest was identified in parboiled brown rice (Table 3). The volume of the monolayer was determined not only by the number of individual components rich in polar positions but also by their physical condition. The hydrothermal influence consisting of parboiling the rice grain was probably the reason for the change in the physical structure of its surface, which contributed to the reduction of the availability of polar positions [7, 16, 35]. As a consequence, if the water content in the tested rice samples is equal, the highest water activity can be recorded in the product R_2. Taking into account that it is not the water content but the water activity that determines the possibility and the dynamics of particular reactions, the product R_2 should be considered to be the most sensitive and to have the lowest storage stability. Therefore, a significantly higher risk of deterioration in quality and loss of safety by R_2 rice was indicated in comparison to R_1 rice when both were transported under similar conditions.

It should be emphasized that if the non-homogeneous cargo with differences in sorption properties is transported in the same conditions (the same level of humidity in the hold), the cargo with a smaller monolayer, aiming to reach a state of equilibrium with the environment, will easily absorb water, but bind it less easily [24]. As a consequence, unbound water will quickly deteriorate its quality and cause the risk of increasing microbial contamination [13, 36].

The values describing the specific surface area of sorption related to investigated rice samples, which were calculated on the basis of the monolayer capacity determined from the BET equation, are also presented in Table 3. Long-grain brown rice (R_1) has the highest specific surface area of sorption, while parboiled brown rice (R_2) has the smallest. The obtained results indicate that long-grain brown rice (R_1) has a high water binding capacity and, therefore, is a stable cargo.

According to the neoclassical economic theory, *homo oeconomicus* should make their decisions rationally, taking into account all available information and following the theory of expected utility, which was described by Ferguson [8]. However, when making decisions, *de facto* managing *inter alia* processes, people are subject to many heuristic prejudices, which deforms the process of thinking or learning. This was demonstrated in 1979 by Daniel Kahneman and Amos Tversky in a series of experiments. Today, it is also known that rational decision-making is often disturbed by falling into cognitive traps. Ferguson mentioned among them *inter alia* availability bias, hindsight bias, the issue of inductive reasoning, conjunction fallacy (or disjunction fallacy), confirmation bias, biased acceptance of evidence, the affect heuristic, observational error, over-reliance on calibration, and the indifference of passive observers [8].

The knowledge management process for identifying risks in maritime logistics supply chains [17] should be based not on recallable information but on information that is genuinely useful. Moreover, events should not be considered more probable after their occurrence (*ex post*) than before their occurrence (*ex ante*). In addition, general rules should not be made on the basis of incomplete information. Another significant problem is overstating the probability of all events with a high probability of occurrence, whereas the probability of occurrence of at least one event with a low probability of occurrence is understating. When implementing management processes in logistics and aiming to improve them, attempts to search for evidence confirming initial hypotheses (the validity of the solutions used so far) should be abandoned. Instead, evidence that undermines hypotheses' correctness should also be taken into consideration. It is also worth mentioning that there is a tendency to allow multiple pieces of information that are irrelevant but related to each other to influence the decision-making process. Moreover, the *a priori* value judgments too often have an influence on the assessment of costs and benefits. In addition, the correct assessment of the costs that need to be borne to avoid considerably more severe damage is also essential in a properly conducted logistic management process. This is the issue discussed in this work. In addition, a balanced amount of confidence in the calibration is necessary, and the role of the confidence intervals, the estimates of which are valid, should be taken into account. Usually, the most favorable scenario is not the most probable. Finally, it should also be taken into consideration that when conducting processes—and, therefore, complex actions—there is a tendency to disclaim individual responsibility as long as these actions take place in an anonymous crowd. In conclusion of the above summary and as a reference to the preliminary results of new research with a high utility for logistics management presented in this study, it should be stated that the issues discussed in this paper will be further pursued and developed.

4. CONCLUSIONS

The results of this work should be the starting point for the process of planning and conducting the maritime transport of rice. They could also be helpful while establishing the storage recommendations, with various degrees of usefulness, connected with transshipment, as well as the packing process and the fulfillment of consumer expectations. Moreover, these results will stimulate further research on the identification of risk factors and the predicting risk level related to the maritime transport of cargo with sorption properties.

1. The water sorption isotherms of all investigated rice types belonged to the type II isotherms. This means that it is a material that undergoes changes related to the impact of certain predictable conditions during transport.
2. The initial water activity in the tested samples taken directly from the ship's hold was at a level that posed a microbiological threat. This exposes the occurrence of negligence at some or many stages of this cargo trade, which increases the risk of deterioration in its quality and safety.
3. The BET equation reflected the sorption data very well for the investigated rice types in the water activity range from 0.05 to 0.44. Therefore, the research procedure presented in this paper and the

use of a simple, theoretical sorption model enable the study of the differentiation of sorption properties important for the stability of dry hygroscopic cargo during maritime transport.
4. Long-grain brown rice has the highest specific surface area of sorption, which makes it the most stable product during storage or maritime transport. Taking this into consideration, it needs to be emphasized that at least some technological procedures (e.g., parboiling) are the primary cause of the increased risk of deterioration in quality and safety during the long-term transport process under the influence of water vapor and water in the form of a liquid.
5. The obtained results suggest that long-grain brown rice (R_1) came into contact with seawater during transport, which was the main reason for the higher water content and activity and, thus, the lack of microbiological stability.

The issues discussed in this article are of particular importance in the event of large-scale natural disasters, as well as armed conflicts.

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Received 14.02.2022; accepted in revised form 05.06.2023