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IDENTIFICATION AND COMPARISON OF HYGROSCOPIC PROPERTIES OF SELECTED VARIETIES OF PEPPER AS AN ELEMENT OF THE STRATEGY FOR REDUCING ITS LOSSES

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Purpose: This study focused on identifying and comparing properties of the raw material, the knowledge of which will help reduce food losses during storage and transport. Its aim was to establish cornerstones for determining differences in pepper quality and safety as affected by storage and transport conditions.

Design/methodology/approach: It entailed the comparison of selected hygroscopic parameters of pepper samples using two sorption models and identifying a correlation between product type and its storage stability. To achieve this aim, the pepper samples were analyzed for water content and water activity, and water sorption isotherms were determined.

Findings: The study results indicate that both the site of pepper cultivation and the processing technology used differentiated its sorption properties and, thereby, its stability in storage and transport conditions. It is recommended to maintain air humidity at 16-27% during transport and storage of pepper.

Research limitations/implications: Findings should be deemed a starting point while planning and implementing pepper transport, and a cornerstone for storage recommendations.

Practical implications: The conducted research yielded results of practical importance. The presented recommendations can be used during the transport and storage of pepper to reduce its losses resulting from the hygroscopic properties of the raw material.

Social implications: Over than 30% of food is wasted annually. In times of dynamically growing population, reducing food losses and waste is important. Significant reductions in it are possible by identifying critical loss points and undertaking targeted actions to optimize production, storage and transport, which was done in this work.

Originality/value: The article presents practical recommendations for spice carriers regarding their transportation and storage conditions. The obtained research results can be the basis for managing the logistics process.

Keywords: pepper; hygroscopicity; BET and GAB models; storage stability; food losses.

Category of the paper: Research paper.

1. Introduction

The FAO reports that 1.3 billion tons of food suitable for consumption is wasted across the globe every year, which accounts for 30% of all food produced (FAO, 2019). Food losses and waste should be treated as a global problem, manifesting itself throughout the entire food chain, from primary production, through postharvest operations, storage, processing, transport and distribution, to consumption in households and restaurants (Łaba et al., 2022). Thus, it may be stated that food losses and waste occur at all links of the food chain; however, the scale of these losses varies. This situation is observed in all countries across the globe, both those striving with chronic malnutrition and excessive consumption (Kwasek et al., 2016). According to preliminary estimates by the FAO, 13.3% of the global food production of 2020 was lost in the first stages of the agri-food chain, i.e., after harvest and before reaching the retail. Only 15% of the food waste came from food processing and as much as 60% from households (Łaba et al., 2020).

Porkka et al. (2013) have pointed out that feeding the world's population is a challenge that will probably become even more complicated in the future than before. In 2018, the world population exceeded 7.6 billion and is expected to reach 9.2 billion by 2050, with a projected 59-102% increase in food demand (Pawlak, Kołodziejczak, 2020). Therefore, reducing food losses and waste in primary production will be an increasingly important issue in the coming decades. It will aim to support a sustainable nutrition model for the growing world population (Nicastro, Carillo, 2021; Buzby, Hyman, 2012), because – from the standpoint of economy – the costs of one ton of wasted food are much higher than the costs of its production (Łaba et al., 2022).

The interest in the issues of food losses and waste observed in recent years has resulted in many definitions of these concepts being found in the literature on the subject. Food loss is defined as the reduction in the quantity or quality of food resulting from the decisions and actions of food suppliers in the agri-food chain, excluding retailers, food service providers and consumers (FAO, 2022). Therefore, empirically, food loss refers to all food that is discarded, burnt or otherwise removed from the food supply chain, i.e., from harvest/slaughter/catch to, but not including, the retail level, and is not reused for other production purposes, e.g., as animal feed. If, for example, grain raw material previously intended for human consumption is used to produce animal feed due to its reduced processing value caused by unfavorable weather conditions or improper storage conditions, it will not be classified as waste or loss. However, if it is ultimately intended for composting, it will be considered wasted food (Łaba et al., 2022). In turn, food waste is defined as a reduction in the quantity or quality of food resulting from the decisions and actions of retailers, catering services and consumers (FAO, 2022).

The first step in preventing food waste is to reduce potential losses. Some food products are not harvested already at the first stage of the agri-food chain, i.e., during primary production, because they fail to meet commercial or quality requirements (Delgado et al., 2021; Parfitt et al., 2010). Primary production is the stage in which the abovementioned phenomena are least recognized and at the same time most difficult to estimate. This is chiefly due to the fact that agriculture depends on variable and unpredictable weather conditions. Crops vary from year to year in their quality, level, product form, and harvest date due to the effects of weather conditions, pests as well as plant and animal diseases. Consumer preferences and needs change as well, as influenced by many economic and noneconomic factors (Świecka et al., 2021). Nonetheless, all the above-mentioned factors contribute to food losses and waste (Borowski, 2018). Some of the losses that occur during transport and storage at farms may be prevented by optimizing production, storage and transport of food products (Kwasek, Łaba, 2020).

Minimizing the scale of the phenomena discussed above is consistent with the implementation of the sustainable development mission, which states that it is the responsibility of the current generation to care for the fate and sustenance of future generations. The United Nations Member States have developed a document called the “2030 Sustainable Development Goals Agenda”, establishing goals with individual targets assigned. Reducing food losses and waste is a key to achieving the 12th Sustainable Development Goal: “Ensure sustainable consumption and production pat-terns”, including its target 12.3: “By 2030, halve per capita global food waste at the re-tail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses” (Kwasek, Kowalczyk, 2023). The essence of the 12th Sustainable Development Goal is to develop a sustainable model of production and consumption. This postulate entails completing many tasks, the first of which concerns reducing food waste by half per capita on a global scale at the retail level, food consumption and limiting losses arising in the production and distribution process. This also applies to limiting losses incurred during the harvest of agricultural produce and appropriate management of the resulting waste (Łaba et al., 2022; Goryńska-Goldman et al., 2021). A significant reduction in food losses is only possible by identifying critical loss points and taking appropriate actions (Garske et al., 2020). To this end, efforts need to be made to collect statistical data at individual stages of the agri-food chain (primary production, harvesting, storage, transport, processing and wholesale) (Kwasek, Kowalczyk, 2023).

This work focuses on identifying and comparing the properties of the raw material, the knowledge of which may contribute to reducing food losses during transport. To achieve these goals, it is necessary to explain the notions of transport and broadly understood logistics. And so, the term logistics has emerged over a hundred years ago and was related to the movement of troops and their supplies (Stevenson, 2010). The logistics approach to the business activities of enterprises was presented in 1955 by O. Morgenster, who defined a logistics operation as providing strictly defined quantities of physical goods and services for specific types of activity (Mroczko, 2016). Today, this term is used to describe all flows of physical goods (Bendkowski, 2013) and covers the entire cycle of preproduction, production and postproduction activities. Therefore, food logistics is an important element in both the food supply chain and meeting consumer requirements as a result of providing the right product, in the required quantity, on time and at low costs, which translates directly into the price offered to consumers (Haij et al., 2020; Jagtap et al., 2021). Its scope includes logistics at ambient and lower temperatures, planning, execution and effective monitoring to meet consumer expectations and reduce losses and waste. In recent years, logistics companies operating in the food industry have mainly implemented IT technologies, which allowed them to improve the management process in the strive for meeting food safety regulations, adapting to changing transport conditions, improving the level of services, but also considering environmental aspects. Customer requirements prompt the implementation of advanced management systems, which is related to, among others, globalization, demographic changes, and demand for personalized food products generally available only at the site of cultivation, or limitations resulting from product's shelf life (Topczewska, Krupa, 2022). The food supply chain includes several phases, from the purchase of agricultural raw materials at the level of primary production through processing, packaging, storage, distribution and redistribution to final consumers (Jagtap et al., 2021). At the same time, sustainable development can be achieved via the implementation of best management practices, innovative technologies allowing for the optimization of transport conditions, and systems related to the improvement of social and environ-mental conditions (Topczewska, Krupa, 2022). The food market in Poland and around the world is subject to continuous improvement. The development of new food production technologies and storage conditions is the cornerstone of the global market evolution. Already implemented, conventional systems enable supervising production conditions and practices, to make the food produced free from any hazards (Malinowska, 2012).

Actions aimed at improving the food supply chain include continuous monitoring and research on the optimal conditions for food transport. Hygroscopic foods represent a particularly interesting group of products. The water present in food determines chemical, physical and biological (including microbiological) changes in its ingredients. The availability of water and its influence on the reactions in food is determined based on water activity (a_w), which is defined as the ratio of the water vapor pressure above the solution to the water vapor pressure above pure water, under conditions of constant temperature and pressure. Water activity affects the consistency, appearance, taste and odor, but above all, the susceptibility of food to spoilage (Ueda et al., 2023). Its continuous control enables achieving the highest quality and maximal stability of food, as well as minimizing the use of food preservatives (Kowalska et al., 2011; Janowicz et al., 2007). The hygroscopic nature of food is associated with the tendency to absorb water in a humid environment or release it in a dry environment, which triggers a change in the water content of a food product. The water vapor adsorption and desorption capacities are product specific features determined by its chemical composition and structure (Domian, Lenart, 2000; Kowalska et al., 2011).

In view of the considerations presented above, this study aimed to identify and compare parameters describing differences in the hygroscopicity of pepper as an inherent feature, critical for its quality and safety. Pepper (Piper nigrum L.) belongs to the group of most known and most frequently used spices in Poland and across the globe. Today, the largest exporters of peppercorns across the world include Vietnam (42.6% of the global production), Brazil (17.5% of the global production) and Indonesia (8.6% of the global production). In turn, the largest importers include the United States (15%), India (10.2%) and Germany (6.3%). According to The Observatory of Economic Complexity (OEC), pepper imports to Poland in 2022 amounted to 1.87% of the global production, accounting for 7.400 t which is 70% of the tonnage of Polish spice imports and 80% of their value. Pepper is imported to Poland mainly from Vietnam (41%), Germany (38.9%) and France (7.67%) (OEC, 2025). This means that the quality of pepper is determined by conditions during a complex logistics process. Typically, this product does not reach the consumer directly from the country where it was produced.

Three pepper types are most often found as utile for transport and cuisine, i.e. black pepper, white pepper and green pepper, all three derived from the same plant species but differing in the production technology of the final spice (Jagella, Grosch, 1999). Pepper becomes a highly hygroscopic product due to the significant reduction in water content after technological processes that make it ready for consumption. Hence, the hygroscopic properties are specific to pepper grains, which are most often transported pepper commodity (Jagella, Grosch, 1999; Kędzia, Kędzia-Hołderna, 2017).

The aim of this study was to establish cornerstones for determining differences in the quality and safety of four different pepper samples during their storage under the same transport conditions. It entailed the comparison of selected hygroscopic parameters of four pepper samples using two sorption models and identifying a correlation between the type of product (including raw material origin and processing technology used), and its stability in transport conditions. To verify the aim of the study, the following research hypotheses were formulated: H_1. The origin of the raw material from which the pepper was obtained significantly differentiates its sorption properties. H_2. The processing technology used for the raw material from which the pepper was obtained significantly differentiates its sorption properties.

2. Materials and Methods

The experimental material included representative samples of black and green pepper from India and Vietnam, purchased in a specialist shop with spices and seasonings in Gdynia, Poland. The quantity of the sample accepted for testing was not less than 2 kg. The test material was stored in non-perforated polyethylene single packages. Pepper is characterized by considerable variability resulting from both heterogeneity in its physical structure and the chemical composition of its corns that determine its sorption properties. Therefore, every pepper sample was first determined for water content and water activity, and results of these determinations were expressed as arithmetic mean and standard deviation from three parallel determinations. The significance of differences between the mean values was analyzed with ANOVA and post-hoc Tukey's test (Łomnicki, 2006).

The initial water content (g H_2O/100 g d.m.) of the samples was determined with the method of thermal drying to a constant mass at temperatures of 373-378 K (100-105°C) under normal pressure, using an SML/30/250 type laboratory dryer (Zakład Aparatury Laboratoryjno-Medycznej ZALMED, Warsaw, Poland) and a WAA 100/C/2 analytical scale (Zakład Mechaniki Precyzyjnej RADWAG, Radom, Poland) (Ocieczek et al., 2021).

Water activity of the samples was determined using an AquaLab 4TE meter (version AS4 2,14.0 2017, Decagon Devices, Inc., Pullman, WA, USA) with ±0.0003 accuracy, at a temperature of 293 K (20°C) ± 2.5 K (Ocieczek et al., 2022).

To achieve reliable results enabling the comparison of the hygroscopicity of pepper samples, sorption isotherms were determined in temperature of 293.15 K (20°C) using the method presented by Flis et al. (2023). Data from these analyses were used to plot sorption isotherms, which describe a correlation between the water content and water activity typical of each dry substance. Graphical models of the isotherms were compared with the Student's t-test of differences between means for bonded pairs. Differences were found statistically significant at $p \leq 0.05$.

Empirical data was explored using two theoretical models: Brunauer, Emmet and Teller (BET); and Guggenheim, Anderson and de Boer (GAB), commonly used to describe sigmoidal isotherms [34].

BET equation (1):

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

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_{BET} – energy constant (Paderewski, 1999; Figura, Teixeira, 2007).

GAB equation (2):

$$v = \frac{v_m C_{GAB} K a_w}{(1 - K a_w)(1 - K a_w + C_{GAB} K a_w)} \tag{2}$$

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_{GAB} – Guggenheim energy constant,
k – constant correcting properties of multilayer molecules compared to the liquid phase (Paderewski, 1999).

Parameters of the analyzed equations were determined based on empirical data, using non-linear regression and Monte Carol algorithm, which enabled avoiding the arrestment of the estimation process by the local minimum. Minimization of root sum of squares (RSS) (3) was assumed as the objective function, as this criterion is most widely applied in the statistical analysis. The root mean square error (*RMSE*) (4), expressed in %, was also used as an equally important criterion in the statistical analysis.

$$RSS = \sum (v_e - v_0)^2 \tag{3}$$

$$RMSE = \sqrt{\frac{\sum(\frac{v_e - v_0}{v_e})^2}{N}} \cdot 100\% \tag{4}$$

where:
N – number of data,
v_e – experimental equilibrium water content (g H_2O/100 g d.m.),
v_o – equilibrium water content predicted with the model (g H_2O/100 g d.m.).

Calculations were performed in Excel 2013 calculating sheet, using a Solver macro-command. Errors in parameters determined for particular equations were estimated with the SolverAid macro-command. The BET model parameters were estimated for a_w range from 0.05 to 0.45, whereas those of the GAB model – for the entire a_w range tested (Andrade et al., 2011).

Knowing the volume of water vapor adsorbed at a temperature lower than the boiling point and the so-called water setting surface, the specific surface area of the adsorbent was computed based on equation 5 (Paderewski, 1999):

$$a_{sp} = \omega \frac{v_m}{M} N \tag{5}$$

where:
a_{sp} – specific sorption area (m^2/g),
N – Avogadro number ($6.023 \cdot 10^{23}$ molecules/mol),
M – molecular weight of water (18 g/mol),
ω – water cross-section area ($1.05 \cdot 10^{-19}$ m^2/molecule).

The size and volume of capillaries of the analyzed material were determined for the capillary condensation area using Kelvin's equation assuming the cylindrical shape of capillaries (Paderewski, 1999; Figura, Teixeira, 2007):

$$\ln a_w = \frac{2\sigma V}{r_k RT} \tag{6}$$

where:
σ – surface tension of the liquid at temperature T (N/m),
r_k – capillary radius (nm),
R – universal gas constant (kJ/mol·K),
T – process temperature (K),
V – molar volume of the adsorbate (m^3/mol).

3. Results and discussion

Sorption properties of spices are the resultant of multiple factors determining the affinity of material surface to vapors and gases. The factors determining the sorption phenomenon, which affect pepper quality and safety during storage also under transport conditions, include water activity and water content. They both determine trends and dynamics of processes occurring during transport (Flis et al., 2023).

The presence of water in the organic matrix is a natural phenomenon. Herein, water occurs in the bound form, incorporated into the structure of matrix particles, and affects their specific character. It may also occur as free water, filling compartments between matrix particles, thereby influencing matrix stability. The initial water content and water activity determine also the nature of the sorption phenomenon, which may follow the pattern of either adsorption or desorption. Results of mean water content and activity of pepper samples are provided in Table 1. The highest water content was determined in black pepper from India (10.87 g H_2O/100 g d.m.), and the lowest one – in green pepper from India (6.92 g H_2O/100 g d.m.). Differences found in water content among the samples were statistically significant, except for the green pepper.

The activity of water, reflecting its thermodynamic state, was the highest in the black pepper from India (0.59), and the lowest in the green pepper from Vietnam (0.47) (Table 1). Differences observed in water activity among all analyzed samples were statistically significant. Since water activity is determined by both the chemical composition and physical structure of particles coordinating water molecules, which in the examined model may differ significantly because of pepper origin and raw material processing technology, it was tentatively established that the sorption of the analyzed products was largely determined by the relationship (expressed as a ratio) between the content of water and water activity it generates.

The analysis of this relationship showed that water molecules entered into strongest reactions with the surface of particles of black pepper from India (18.58). In turn, the water molecules exhibited the weakest affinity to the particles of green pepper from India (13.74). It was also found that the water-matrix interaction was stronger in the case of black pepper (18.58 and 17.91) compared to green pepper (15.07 and 13.74), regardless of raw material origin. Results of investigations on sorption properties and storage stability of ground pepper available in retail showed it had a higher water content and water activity, on average, compared to the pepper grains (Ocieczek et al., 2020).

Table 1.
Initial water content and activity in the analyzed pepper samples

Product	Parameters	
	Initial water content ± SD ($g\ H_2O/100\ g$ d.m.)	**Initial water activity ± SD (-)**
Black pepper from India	10.8724 ± 0.2486^{c}	0.5851 ± 0.0012^{d}
Green pepper from India	6.9158 ± 0.3945^{a}	0.5035 ± 0.0114^{b}
Black pepper from Vietnam	9.8476 ± 0.1908^{b}	0.5497 ± 0.0018^{c}
Green pepper from Vietnam	7.0539 ± 0.1374^{a}	0.4682 ± 0.0056^{a}

Explanatory notes: Table shows mean values ± standard deviations; mean values denoted by different letters differ statistically significantly at $p \leq 0.05$.

Source: own research.

Water activity of all analyzed samples ensured their storage stability, as it was lower than 0.6, which is a value deemed critical for the microbiological safety and stability of food products since $a_w < 0.6$ of food prevents microbiota development. The minimal aw values for the development of bacteria, yeast and most molds have been reported at 0.9, 0.8 and 0.7, respectively (Tapia et al., 2020). Food products are the most stable at aw ranging from 0.07 to 0.35 and water content ranging from 2 to 15%. The present study results indicate that the analyzed samples were microbiologically safe and stable, which is particularly important given the possibility of presence of various microorganisms on pepper particles. It needs to be emphasized, however, that such products should be considered as metastable under the environmental conditions, including primarily water vapor presence in the air.

Technological operations typical of black pepper production do not include processes which potentially increase water content and, consequently, water activity; hence, the relatively high water content determined in black pepper in the present study cannot be attributed to the production technology. It may be hypothesized that it could be due to inappropriate transport and/or storage conditions. Pałacha and Malczewska (2010) achieved similar results of initial water activity and water content of black pepper samples. Therefore, the state of a product such as pepper does not depend only on the properties of the raw material and the parameters of the technological process. It can change many times due to the influence of environmental conditions and should be treated as metastable.

Figure 1 presents the course of water sorption isotherms plotted for the analyzed pepper samples. The points describing sorption isotherms represent mean values of measurements, whose variability coefficients ranged from 0.06% to 1.3% for black pepper from India, from 0.01% to 0.25% for green pepper from India, from 0.03% to 2.4% for black pepper from Vietnam, and from 0.01% to 0.42% for green pepper from Vietnam.

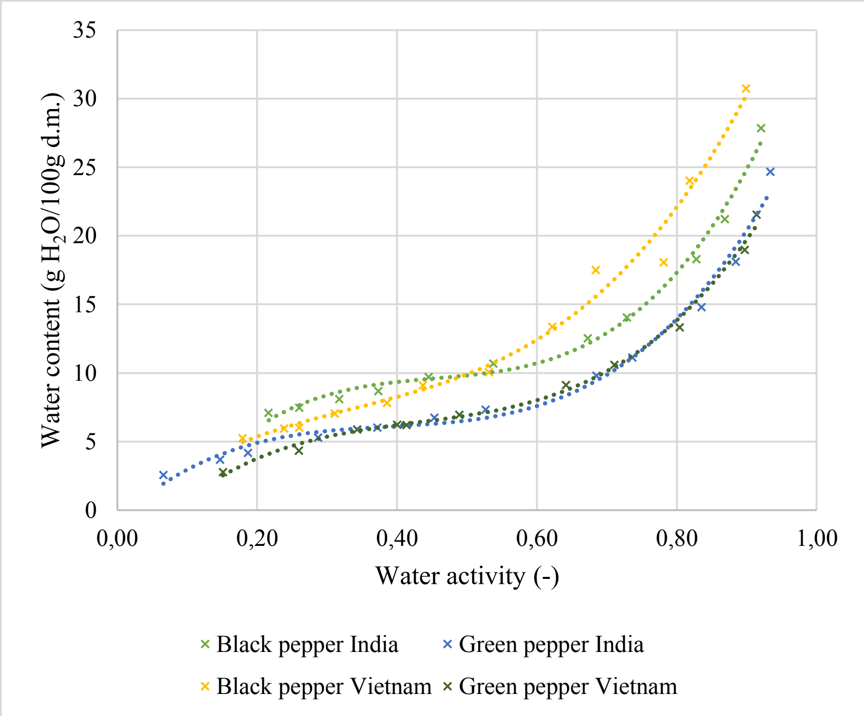

Figure 1. Isotherms of water sorption in the analyzed pepper samples.

Source: own research.

The course of water sorption isotherms plotted for all analyzed pepper samples allows concluding that they were strongly hygroscopic materials capable of absorbing high volumes of water. Regardless of pepper type, the plotted water sorption isotherms had a typical sigmoidal shape, characteristic for type II isotherms acc. to classification by Brunauer et al. (1938). Type II isotherms are typical of food products rich in starch, protein or their mixtures. This shape of isotherms indicates that water sorption proceeded in three stages.

Graphical evaluation of the course of sorption isotherms demonstrated that green pepper samples were more similar to each other than the black pepper samples in terms of their hygroscopicity. This finding may suggest that the technological process applied to produce green pepper from raw material had a significantly stronger impact on its native traits compared to the technological operations applied during black pepper production. In contrast, the statistical analysis of sorption isotherm course data showed that the samples differed from each other in their hygroscopicity to a various extent. The results of Student's t-test for differences between mean values for bonded pairs enabled concluding that these differences were statistically significant.

Another and a more advanced means allowing not only to identify but also compare hygroscopicity, based on specified parameters expressed in numerical values, is the presentation of isotherms using parameters of mathematical models. In the present study, water vapor sorption isotherms were described with two theoretical sorption models: Brunauer, Emmet and Teller (BET); and Guggenheim, Anderson and de Boer (GAB) (Ocieczek et al., 2020).

The BET equation is a theoretical model that filled the gap in the interpretation of sorption isotherms and therefore has been accepted as a general method for determining the surface area of adsorbents from sorption data (Ocieczek et al., 2021). The choice of the classical BET model was driven by the fact that, despite its limitations, it is still used for monolayer calculations in various areas of physicochemical research, owing to which the results achieved may be compared. Moreover, this model is approved by the International Union of Pure and Applied Chemistry (IUPAC) (Flis et al., 2023). Due to its linear form, which unfortunately tends to overestimate the predicted amount of vapor adsorbed by the sorbent under high pressure, the BET model is an effective tool for estimating the amount of water bound in specific polar regions. Therefore, taking into account its limitations, it was used to describe the studied phenomenon in the water activity range of 0.07 to 0.45, which is indicated in the literature as the range of its utility (Andrade et al., 2011). The model parameters and the degree of its fit to the empirical data are expressed as the root sum of squares (*RSS*) and root mean square error (*RMSE*) and presented in Table 2.

Table 2.
Parameters of the BET equation for the analyzed pepper samples

Product	C_{BET} (kJ/mol)	v_m (g H_2O/100 g d.m.)	a_w corresponding to v_m (-)	*RSS* (-)	*RMSE* (%)
Black pepper from India	1.66E+11±1.40E+19	5.4704±0.0444	0.1671	0.0524±0.1619	1.23
Black pepper from Vietnam	15.0041±4.8897	5.4743±0.2701	0.1982	0.1322±0.25711	2.49
Green pepper from India	22.6004±4.9103	4.0131±0.1074	0.1751	0.1108±0.2354	2.90
Green pepper from Vietnam	3.5475±1.3832	0.5266±0.3405	0.0287	0.4969±0.4985	6.62

Source: own research.

The comparison of *RSS* pointed to a relatively good fit of the model to empirical data. However, taking into account the limitations of this indicator in assessing model's fit to empirical data, the values of the root mean square error (*RMSE*) were estimated as well. Assuming that an *RMSE* value of less than 10% indicates good fit of the model to empirical data in the selected range of water activities, the BET model was found to well describe the experimental data of all pepper samples. Thus, the generated parameters of the BET model can be considered reliable and comparable, and their interpretation gains application value.

Similar results of BET model fitting to empirical data describing the sorption isotherms of ground pepper available in retail were obtained by Ocieczek et al. (2020).

Relatively low values of the energy constant (C_{BET}) estimated for 3 of the 4 analyzed samples enable concluding that the investigated process was physical in nature and that the identity of the adsorbed water molecules did not change significantly. The very high C_{BET} estimated for one of the samples can probably be attributed to the mathematical compensation of its value performed in order to obtain an optimal solution for the remaining parameters (Andrade et al., 2011).

The second of the estimated parameters was the capacity of the monomolecular layer (v_m). Its highest value was determined in both samples of black pepper, whereas a considerably lower one – in the green pepper samples (Table 3). Consequently, the results obtained and a critical analysis of the literature (Kędzia, Kędzia-Hołderna, 2017; Ocieczek et al., 2020; Flis et al., 2023) enable formulating conclusions being of practical importance when optimizing actions aimed at stabilizing the quality and safety of pepper during its maritime transport. The key conclusion is that with the same water content of all analyzed pepper samples, the highest water activity will be determined in green pepper. Assuming that the average water content of green pepper samples was 7 g H_2O/100 g d.m., as shown by the initial water content analysis, it may be concluded that their water activity will reach 0.6, which is deemed a critical level for the microbiological safety. Meanwhile, although the average water content of black pepper was 10 g H_2O/100 g d.m., it generated water activity of 0.55, which prevents the proliferation of microorganisms. Given the fact that it is not the water content but its activity that determines the possibility of occurrence and dynamics of certain reactions, black pepper should be considered more stable during storage and safer for consumers, even if it was periodically stored under unfavorable conditions during transport.

Because the BET model is a special case of the GAB model (Kludsky et al., 2018) and because it has certain limitations in describing sorption isotherms, the sorption parameters were estimated also based on the GAB model (Tab. 3), the use of which requires a broader range of data (a_w < 0.93). The application of the GAB model to food sorption isotherms shows a good fit up to a_w = 0.9. The simplicity and physical meaning of the GAB model makes it very useful for describing and interpreting water sorption isotherms for food. The GAB model values are more general and have more physical meaning (Timmermann, 2003).

Table 3.
Parameters of the GAB equation for the analyzed pepper samples

Product	C_{GAB} (kJ/mol)	v_m (gH_2O/100g d.m.)	*K* (-)	a_w corresponding to v_m (-)	*RSS* (-)	*RMSE* (%)
Black pepper from India	1.49E+10± 1.83E+18	5.4964± 0.2080	0.8632± 0.0114	0.1679	5.3081± 0.8146	5.41
Black pepper from Vietnam	9.7869± 7.1055	6.3731± 1.0764	0.8953± 0.0526	0.2778	11.4414± 1.1959	6.43

Cont. table 3.

Green pepper from India	43.7173± 26.6214	3.8121± 0.1494	0.9023± 0.0080	0.1601	2.1048± 0.5129	7.59
Green pepper from Vietnam	15.7816± 8.0414	4.1832± 0.2663	0.8788± 0.0139	0.2499	2.1120± 0.5138	9.17

Source: own research.

The *RSS* values were compared analogously to the procedure for assessing the BET model suitability for describing the obtained data, and this comparison showed a good fit of the model to the empirical data. This was confirmed by the estimated *RMSE* values, which were lower than 10% for all samples. Comparison of these results indicates that the GAB model described all sets of results more evenly than the BET model, which makes the obtained estimates more reliable. Therefore, the interpretation of the GAB model parameters has an application value. Similar results were obtained in studies carried out with ground pepper (Ocieczek et al., 2020).

According to Lewicki (1997), the energy constant (C_{GAB}) should exceed 5.67, which is one of the prerequisites of this model's applicability. This condition was met in all samples analyzed in the present experiment. The significantly higher energy constant (C_{GAB}) estimated for the black pepper from India was, most likely and similarly to the BET model, due to the mathematical compensation of its value. At the same time, there are no additional indications that the investigated process was of a non-physical nature and that the identity of the adsorbed water molecules was modified to a significant extent (Lewicki, 1998).

The K values were higher than 0.24, which according to the findings made by Lewicki (1997), is the second condition for the applicability of the GAB model and indicates that the GAB equation was correctly applied to describe the present experiment.

In turn, the values describing the monolayer capacity (v_m) based on the GAB model confirm that black pepper grains, regardless of the origin of the raw material they were produced from, showed a greater affinity for water and capability for its strong coordination. This makes this pepper more stable under unfavorable storage conditions determined by a high water content of the air.

The last part of the study entailed estimation and comparison of parameters describing the microstructure of the surface of the analyzed pepper grains (Table 4).

Table 4.
Characteristics of the surface microstructure of the analyzed pepper samples

Product	Specific sorption area (m^2/g)		Total volume of capillaries (mm^3/100 g d.m.)	Capillary radius filled at $a_w = 0.6$ (g H_2O/100 g d.m.)
	BET	GAB		
Black pepper from India	192.2	193.1	107.32	1.38
Black pepper from Vietnam	192.3	223.9	114.86	3.86
Green pepper from India	141.0	133.9	87.49	0.99
Green pepper from Vietnam	18.5	147.0	82.56	1.01

Source: own research.

The first analyzed parameter of microstructure was the specific sorption surface area, which was calculated based on the size of the monolayer determined from the BET and GAB equations. Black pepper had a larger specific sorption surface area compared to the other samples. Moreover, the total capillary volume was estimated using the GAB model and based on data from the range corresponding to the capillary condensation area. This parameter indicates the amount of water that will fill the capillaries and will constitute the fraction of structured water with a high activity. The results indicate that the surface of black peppercorns was more porous than that of green peppercorns. Next, the radiuses of the capillaries that were filled after the beginning of the capillary condensation phenomenon were estimated using the Kelvin's equation. The results indicate that the black pepper from Vietnam had the most open structure, allowing it to effectively bind large amounts of water when its content in the atmosphere increases.

The above findings are particularly important given the fact that pepper is usually transported by sea, which entails its relatively long-lasting exposure to water in the form of both vapor and liquid. Such conditions usually trigger changes in product quality, primarily due to increased microbial counts and the accumulation of their metabolites, which are often toxic to the human body. Therefore, it is very important to state that these changes can occur in seemingly similar products (green and black pepper from different regions of the world) under the influence of the same conditions but with different dynamics and to a different extent. Therefore, it should be emphasized that the quality of pepper as a commodity available on the global market is largely determined by the conditions of its storage during transport (Hammouti et al., 2019). It should also be noted that the quality of any product is not a constant parameter, and this is particularly true for pepper and similar products, such as cereals, which are traded on a mass and global scale.

Meanwhile, in logistics processes, attention is paid mainly to whether the goods arrived at the destination within the specified time, while no consideration is given to its quality, which in the case of food includes primarily safety for consumers. Emphasizing this aspect is important because in the case of pepper, as a product characterized by a compact structure and a low water content, it is very often difficult to notice signs of spoilage, while its level of safety is very questionable. Therefore, although the literature in the field of logistics indicates the need to implement advanced management systems (Topczewska, Krupa, 2022), the present study results enable concluding that sustainable development can only be achieved by using knowledge from natural and technical sciences in management processes.

Managing logistics processes in which food is the object of the process requires specialist knowledge and acquaintance of new technologies that allow optimizing transport conditions. Considering the management process only as activities related to the transfer of information and its collection on paper or even electronic media has exhausted its possibilities. It is necessary to take a step back, i.e., return to the implementation of the best management practices in engineering. The results of engineering works will be a driving force for further progress in achieving the concept of sustainable development because they allow making rational decisions whose effects will be measurable. Transferring responsibility to other elements of the system (e.g., insurance) in an increasingly complex system does not solve anything (Flis et al., 2023). Problems should be solved where they arise, and not be just pushed away. The food market is continuously improving, while novel food production technologies and storage conditions underlay the evolution of the global food market. Therefore, it should be emphasized that the education of management specialists, i.e., engineers with thorough knowledge from natural sciences and technology, will pose a real challenge for the modern world.

4. Conclusions

The results obtained in this study should be a starting point when planning and implementing pepper transport by sea, as well as storage recommendations of varying degrees of usefulness, related to: reloading works, the packaging process and, ultimately, the pursuit of meeting consumer expectations. Optimizing logistics processes for pepper can significantly reduce cargo losses and, therefore, food losses and waste. They are also a cornerstone for further research aimed at identifying risk factors and estimating its level related to the transport of loads with sorption properties, especially in various temperature conditions.

The results obtained during the research allowed for a positive verification of both research hypotheses. H_1. The origin of the raw material from which the pepper was obtained significantly differentiates its sorption properties. H_2. The processing technology used for the raw material from which the pepper was obtained significantly differentiates its sorption properties. The analysis of the results obtained using both models indicates that Water vapor sorption isotherms of all tested types of pepper could be considered type II sorption isotherms, according to the classification of Brunauer and colleagues. This means that pepper represents a material with predictable quality changes related to the impact of the environment with specific parameters during transport. The initial water activity determined for both black pepper samples tested was at a level that did not pose any microbiological hazard. This does not mean, however, that the microbiological and toxicological quality of the tested material was satisfactory. Both mathematical models used described the sorption data for the tested types of pepper very well. This means that the research procedure presented in this work allows identifying differences in the sorption properties important for the stability of dry hygroscopic cargoes during transport. Black pepper from India had the greatest specific sorption surface area, which made it the most stable product during storage or transport. The obtained results allow concluding that both the site of pepper cultivation and the processing technology used differentiate its sorption properties and, therefore, its stability in transport conditions.

It is recommended to maintain air humidity at 16-27% during transport and storage of pepper, this value should be constantly monitored using digital hygrometers.

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