Comparison of the Sorption Properties of Fruit Powder Shampoos Using the BET, GAB, and Peleg Models

Aneta Ocieczek and Małgorzata Zieba*

Abstract: The aim of the study was to employ BET, GAB, and Peleg models for mathematical description of sorptive properties of market powder shampoos of natural origin. Two commercial powder shampoos of plant origin *Sapindus mukorossi* (A) and *Acacia concinna* (B) were used as study materials. The sorption isotherm of *A. concinna* powder shampoo was much higher in the standard reference system in comparison to *S. mukorossi* shampoo. The B shampoo had a higher monolayer capacity than product A. The examined process in both cases was physical in nature. The most useful for isothermal description turned out to be the theoretical BET equation and empirical Peleg model. They were characterized by high accuracy. Natural powder shampoos differed significantly in terms of physical parameters of particles and sorptive properties, which may suggest their different functional properties.

1. INTRODUCTION

The powder form of shampoos offers an interesting alternative to standard liquid cosmetics for hair washing. The advantages of the powdered form certainly include reduction or elimination of preservatives and stabilizers (radically reduced water content significantly inhibits the proliferation of microorganisms), ease of storage and convenience of transport with no possibility of weight loss due to product spillage, and reduced use of packages due to the concentrated form of a product, which should be mixed with water before use.1

Multiple methods can be used to determine the functional properties of standard shampoos,1−3 whereas there are no standard guidelines set for the powder shampoos that could be used by their manufacturers to verify their quality. Usually, in industrial practice, powder shampoos produced on the basis of ground vegetable materials are packed when the powder does not tend to clump. However, the water content similar to that which causes clumping is already very high and not only makes it difficult to use such a powder but also exposes the user to contact with microorganisms. With such a high water content, microorganisms, especially molds, may multiply or produce toxins, which are their metabolites formed in conditions of still tolerated water deficiency.4 At the same time, it should be stressed that excessive dehydration of the shampoo powder will favor oxidative reactions, which limit the health-promoting properties of the shampoo powder obtained from natural raw materials. Moreover, unjustified dehydration of the powder leads to an increase in the cost of its production and at the same time burdens the environment.

This urges the need for developing novel research methodologies or for adapting these already employed in other industry branches. Our previous study1 demonstrated the feasibility of implementing the methodology used mainly for the assessment of powdery food products into the evaluation of powder shampoos.

Experimentally plotted sorption isotherms can be subjected to mathematical description using various models. The product’s structure and sorptive phenomena are usually described based on theoretical BET and GAB models as well as empirical models, e.g., the Peleg model. This study aimed at employing theoretical models BET and GAB and an empirical Peleg model for the mathematical description of adsorption isotherms determined experimentally for commercial powder shampoos.

2. RESULTS AND DISCUSSION

Water vapor sorption by solids depends upon many factors, among which chemical composition, physical–chemical state of ingredients (such as the degree of denaturation or cross-linking), and physical structure are the most important. These
parameters determine substantially the quantity of sorbates absorbed and the kinetics of the sorption process. The powder shampoos constitute a mixture of particles differing in selected physical characteristics (Table 1) that can potentially affect these particles’ interactions with water molecules (hydration properties), including also their sorptive properties. The latter properties may, in turn, determine not only the performance properties but may also destabilize its durability. Summing up, it can be concluded that the analyzed powder shampoos differ in the physical parameters of their particles. Differences in particle shape are also indicated by the mean value of the shape coefficient, which was higher in the case of particles of shampoo A (~0.69) than in shampoo B (~0.63). The last analyzed shape parameter was the distribution of particle solidity. Its mean value was higher in the case of shampoo A than in shampoo B. Worthy of notice is also the lower value of the standard deviation, which points to the stability of this trait (solidity) in the case of shampoo A particles. A comparison of the physical parameters of the particles of both shampoos tested indicates that B shampoo will show a tendency to self-sort, i.e. to divide into fractions under the influence of vibrations. This in turn will worsen its performance properties but may also destabilize its durability. Summing up, it can be concluded that the analyzed powder shampoos differed in the physical parameters of their particles. The particles of shampoo B were characterized by greater differences in their size and by irregular shapes manifested in multimodality. These parameters can play a significant role in modeling the functional characteristics of shampoos during their hydration. In addition, they can cause differences in the storage stability of these products. Better quality attributes are to be attributed to A shampoo. The porous structure of grains (particles) in chemical engineering is referred to as adsorbent texture. Regardless of the chemical nature of the substance of which the adsorbent is composed, it has a high sorption absorbency

Table 1. Selected Physical Characteristics of the Tested Powder Shampoo Samples

| characteristics                                      | parameter            | A (counted particles n = 147368)                                                                 | B (counted particles n = 283465)                                                                 |
|-----------------------------------------------------|----------------------|------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| diameter value distribution (μm)                    | min. | max. | mean ± SD | D[n, 0.1] | D[n, 0.5] | D[n, 0.9] | min. | max. | mean ± SD | D[n, 0.1] | D[n, 0.5] | D[n, 0.9] |
| circularity value distribution                       | 0.031 | 1.000 | 0.744 ± 0.159 | 0.512 | 0.780 | 0.909 | 0.029 | 1.000 | 0.661 ± 0.203 | 0.356 | 0.697 | 0.899 |
| elongation value distribution                        | 0.000 | 0.947 | 0.306 ± 0.154 | 0.112 | 0.293 | 0.514 | 0.000 | 0.936 | 0.369 ± 0.166 | 0.148 | 0.365 | 0.592 |
| shape coefficient value distribution                 | 0.053 | 1.000 | 0.694 ± 0.154 | 0.484 | 0.705 | 0.886 | 0.064 | 1.000 | 0.631 ± 0.166 | 0.406 | 0.633 | 0.849 |
| solidity value distribution                          | 0.188 | 1.000 | 0.936 ± 0.072 | 0.840 | 0.952 | 0.990 | 0.177 | 1.000 | 0.906 ± 0.109 | 0.724 | 0.926 | 0.989 |

Figure 1. Sorption isotherms of tested shampoos A and B.
due to its pore network. The pore diameters of adsorbents vary widely, ranging from a few tens to several hundreds of nanometers. Rarely are adsorbents monodisperse.\(^8\) In most cases, they have pores of different diameters, particularly for particles resulting from the grinding of substances of biological origin. The size and energy of adsorption related to the unit of mass of the adsorbent depend not only on the nature of the surface of the adsorbent and the adsorbed particle but also on its texture.\(^9\) Pores may vary in size and shape. Provided that the surface of the adsorbent and the adsorbed particle but also on the mass of the adsorbent depend not only on the nature of the origin. The size and energy of adsorption related to the unit of particles resulting from the grinding of substances of biological respectively.

The empirically determined data describing the course of sorption isotherms allowed determination of the parameters of the GAB model (Table 3). The RSS and RMS values obtained demonstrate inferiority of the GAB equation in characterizing water vapor adsorption on the surface of shampoo B than shampoo A particles, although the fit of the model to the primary data in both cases is highly satisfactory.

A comparison of RSS and RMS values indicates that the BET equation much better characterizes water vapor adsorption on the surface of shampoo B than shampoo A particles, although the fit of the model to the primary data in both cases is highly satisfactory.

The monolayer capacity \((v_m)\) determined using the BET equation describes the sorptive capacity of adsorbents as well as the availability of polar sites for water vapor. A higher monolayer capacity was demonstrated for shampoo B particles, which can be explained by the presence of a high number of hydrophilic functional groups capable of interacting with water molecules. Karel\(^13\) demonstrated the water content of the monolayers of various products of natural origin (e.g., food) to range from 4 to 11 kg H\(_2\)O/100 kg d.m., while a slightly wider range of these values was reported in the present study.

In turn, values of the energy constant \(C\) fitted within the range of 0.8366 to 1.2125, which may point to a similar course of the sorption phenomenon on the surfaces of both powders and also to the physical nature of the process, in the case of which the enthalpy value is at approximately 20 kJ/mol.\(^14\) It should be emphasized that such a small enthalpy change usually does not affect the identity of the physically adsorbed molecules.

An analogous scheme was adopted when determining parameters of the GAB model (Table 3).

The RSS and RSM values obtained demonstrate inferiority of the GAB equation in characterizing water vapor adsorption on the powder particle surface compared to the BET model. The GAB model allowed for more precise description of the sample of shampoo A than shampoo B.

In addition, it needs to be emphasized that values of water content of the monolayer \((v_m)\) determined using the GAB equation were negligibly higher than those obtained with the BET model.

Values of the Guggenheim constant of energy \(C\) are indicative of the hygroscopic nature of the product. Lower values of \(C\) constant were determined for shampoo A, which points to a lower amount of heat released from the product during the sorption process. The analysis of \(C\) values allows us to conclude that the usability of the GAB model for the description of experimental data cannot be undermined in the case of both shampoos. According to Lewicki,\(^15\) at values exceeding 5.67, this parameter confirms the right choice of the GAB model for empirical data description. This condition was met in both cases in our study. As claimed by Diosady et al.,\(^16\) the strong exothermal interactions between the adsorbent and the adsorbate can lead to a decrease in process temperature and to higher \(C\) values. Results of the present study demonstrate that the process of surface adsorption of water

---

**Table 2. Parameters of the BET Equation for the Powder Shampoo Samples Tested**

| parameter | shampoo A | standard error | shampoo B | standard error |
|-----------|-----------|----------------|-----------|----------------|
| \(v_m\)   | 3.0399    | ±0.8446        | 6.8083    | ±0.1396        |
| \(C\)     | 1.2125    | ±0.2400        | 0.8366    | ±0.0130        |
| RMS       | 3.3831    | ±0.2616        | 0.2616    | ±0.0328        |
| RSS       | 0.2347    | ±0.3426        | 0.0021    | ±0.0328        |

**Table 3. Parameters of the GAB Equation for the Powder Shampoo Samples Tested**

| parameter | value | standard error | parameter | value | standard error |
|-----------|-------|----------------|-----------|-------|----------------|
| \(c\)     | 6.7855| ±4.7853        | \(c\)     | 19.6394| ±36.8122       |
| \(K\)     | 0.9472| ±0.0433        | \(v_m\)   | 0.8159| ±0.1305        |
| \(v_m\)   | 5.5579| ±0.9621        | \(v_m\)   | 7.8335| ±2.4468        |
| RMS       | 11.3660| ±0.1140     | RMS       | 13.8918| ±2.5886        |
| RSS       | 7.0647| ±1.1887        | RSS       | 33.5050| ±2.5886        |

---

https://doi.org/10.1021/acsomega.0c00851

ACS Omega 2020, 5, 14354−14359
by particles of the analyzed powder shampoos was physical in nature.

Values of the $K$ parameter serve to correct properties of molecules constituting the multilayer in relation to the liquid phase. The analysis of the $K$ values obtained showed that they were relatively similar in both samples, which allows us to hypothesize that the energy status of the water molecules constituting the multilayer system was similar in both samples. In addition, the value of the parameter $K$ can be analyzed in terms of the feasibility of using the GAB model for the description of surface phenomena because Lewicki demonstrated that, when values of the $K$ constant fit within the range of $0.24-1$, the error of estimation of water content in the monolayer at $\pm15.5\%$ requires the $C$ constant value to exceed $5.5$. This condition was met in both samples. In addition, the value of the $K$ constant allows identification of a difference between the monomolecular ($K \leq 0.5$) and multilayer ($K > 0.5$) adsorption. However, results of some research show that the $K$ value depends on the predominance of one of the macromolecules of natural origin. The predominance of protein structures was found to correlate with $K$ constant values in the range of $0.82-0.86$, while the predominance of starch structures was found to correlate with $K$ values of $0.7-0.77$. Considering the specific character of the analyzed material, all $K$ values obtained should be treated as resulting not only from the interactions ongoing during water molecule adsorption by the heterogeneous structure of the disintegrated natural material but also from differences in the physical state of the molecules.

The knowledge about sorption isotherms allows also for the theoretical analysis of the microstructure of the material surface. Estimating monolayer capacity (Tables 2 and 3) using the theoretical BET or GAB model enables determination of the specific surface area of sorption (Table 4), whereas the GAB model additionally enables determination of such microstructural parameters of the surface of the examined particles as volume of capillaries and radius of capillaries, which are filled after capillary condensation was initiated (Table 4).

Results of analyses of the microstructural surface characteristics demonstrate that the specific surface area depended on both material type and physical differences between particles associated with their disintegration (fraction size). A more developed sorption surface was observed for the powder particles of shampoo B. This means that its particles exhibited greater affinity to water, due to which a moderately higher volume of water would not cause a significant increase in water activity, which in turn will positively affect storage stability of the powder by inhibiting microbiological and hydrolytic changes. The other results obtained demonstrate that the powder of shampoo B was also characterized by a higher total volume of capillaries and by a greater radius of capillaries filled at the moment of initiating the phenomenon of capillary condensation than the powder of shampoo A. These results allow us to hypothesize that the higher total volume of capillaries of the shampoo B powder was mainly due to the larger sizes of its capillaries.

The last model used for the description of sorption isotherms plotted for powder shampoos was the four-parameter Peleg model in 1993, which is characterized as an empirical equation devoid of an empirical background. In most research works, it is indicated as a model with similar or even higher usability for water vapor sorption description compared to the GAB model. Its parameters are presented in Table 5.

Table 5. Parameters of the Peleg Equation for the Powder Shampoo Samples Tested

| Shampoo | Parameter | Value | Standard Error |
|---------|-----------|-------|----------------|
| A       | A         | 10.8028 | ±1.0300 |
| B       | B         | 0.2741  | ±0.0698 |
| A       | D         | 47.4942 | ±3.2987 |
| B       | E         | 4.9875  | ±0.4411 |
| A       | RMS       | 1.6395  |               |
| B       | RSS       | 0.6087  | ±0.3901 |

Considering the fit of the Peleg model to empirical data, the RSS and RMS values obtained allow us to conclude that this model described the sorption phenomenon better than the GAB model and worse than the BET model. Values of the goodness-of-fit parameters show also that this model proved to be very well in experimental data description regardless of the characteristics of powders being influenced by the type of material they are made of. In addition, a comparison of Peleg equation parameters, considering their estimation errors, indicates that the powders tested differed significantly in their sorptive properties (hygroscopicity).

A comparative analysis of the statistics used to evaluate predictive capability of the models tested demonstrated the BET and Peleg models to meet the criteria, which indicate their good fit to experimental data. However, considering the theoretical nature of the BET model, it is found to be more useful in studies on the surface phenomena ongoing in a dehydrated matrix of natural origin.

3. SUMMARY AND CONCLUSIONS

An attempt was undertaken in this study to employ theoretical models BET and GAB and an empirical Peleg model for the mathematical description of sorption isotherms plotted experimentally for commercial powder shampoos. Two commercial natural powder shampoos were selected for the study: shampoo A made of fruits of *S. mukorossi* and shampoo B made of fruits of *A. concinna*.

The following conclusions were formulated based on the analysis of study results:

The sorption isotherm of powder shampoo B was much higher in the standard reference system than that of powder shampoo A. Parameters of the theoretical equations (BET and GAB), used to describe sorptive properties of shampoos, demonstrated a higher monolayer capacity of shampoo B than shampoo A. In the case of both shampoos, the sorption process...
was physical in nature, whereas powder B was characterized by a more open surface microstructure, which could be one of the significant reasons behind its better sorptive properties.

Information about water status in the powder shampoos tested was verified based on sorption isotherms. The theoretical BET equation and the empirical Peleg model turned out to be the most useful for isotherm description. Both were highly accurate in empirical data description, as indicated by low RSS and RMS values.

The advanced hypothesis was positively verified because the natural powder shampoos examined differed significantly in their sorptive properties, which may additionally indicate differences in their functional characteristics.

4. EXPERIMENTAL SECTION

The experimental material included natural powder shampoos of plant origin, i.e., shampoo A — a natural powder shampoo made of *S. mukorossi* fruits, and shampoo B — a natural powder for hair washing made of *A. concinna* fruits.

The particle size analysis of the tested powder shampoos, including fraction size distribution and fraction shape distribution, was conducted using an automated Morphology G3 analyzer (Malvern Instruments, Great Britain), which enables measurements of distribution of solid particles with sizes ranging from 0.5 to 1000 μm. Determinations included distributions of values of parameters such as diameter, circularity, elongation, shape coefficient, and solidity.24

The sorption isotherms were determined with the static-desicator method, which is based on the evaluation of the humidity balance between a tested sample and the atmosphere with a given relative humidity regulated by saturated solutions of respective substances: NaOH (0.0698), LiCl (0.1114), CH3COOK (0.2310), MgCl2 (0.3303), K2CO3 (0.4400), Na2Cr2O7 (0.5480), KJ (0.6986), NaCl (0.7542), KCl (0.8513), and KNO3 (0.9320). Analyses were conducted at a balance was 90 days after the samples were placed in a desiccator. Detailed description of the research methods was provided in the literature.25

Differences in the course of sorption isotherms across the entire *a* range were analyzed statistically using Student’s *t* test for differences between the means of matched pairs. Differences were considered statistically significant at a significance level not exceeding *P* = 0.01. The choice of this test was determined by the specificity of the study, analogous to agricultural studies, in which the samples are bound with a common “field”, in this case a desiccator.

The BET equation used in the study was as follows

\[
\nu = \frac{\nu_{m} C a_{w}}{(1 - a_{w})[1 + (C - 1)a_{w}]} \tag{1}
\]

where *a* is the water activity (−), *ν* is the equilibrium water content (g H2O/100 g d.m.), *νm* is the water content in the monolayer (g H2O/100 g d.m.), and *C* is the energy constant.22,23

The GAB equation used in the study was as follows

\[
\nu = \frac{\nu_{m} CK a_{w}}{(1 - Ka_{w})(1 - Ka_{w} + CK a_{w})} \tag{2}
\]

where *C* is the Guggenheim energy constant and *K* is constant correcting properties of multilayer molecules compared to the liquid phase.22,23

The Peleg equation used in the study was as follows

\[
\nu = A a_{w}^{B} + D a_{w}^{E} \tag{3}
\]

where *A*, *B*, *D*, and *E* are constants.

The parameters of the equations were determined on the basis of empirical data using nonlinear regression with a Monte Carlo algorithm, which prevented inhibition of the estimation process by a local minimum. This criterion is most frequently used in statistical analysis.24 Calculations were performed in Excel 2007. Residual sums of squares (RSS) of the determined parameters of the BET, GAB, and Peleg equations were estimated using the SolverAid macro command based on the Hesse matrix. The usability of the models tested for the description of experimental data was evaluated based on the root mean square (RMS) error expressed in %.

\[
\text{RMS} = \sqrt{\frac{\sum (\nu_{e} - \nu_{p})^{2}}{N}} \times 100 \tag{4}
\]

where *N* is the number of data, *νe* is the experimental equilibrium water content (g H2O/100 g d.m.), and *νp* is the predicted equilibrium water content (g H2O/100 g d.m.).

Knowing the volume of water vapor adsorbed at a temperature lower than the boiling point and knowing the so-called water cross-section area, the specific surface area of the adsorbent was computed based on the following equation

\[
a_{vp} = \frac{\nu_{m} N}{M} \tag{5}
\]

where *a* is the specific sorption area (m2/g), *N* is Avogadro’s number (6.023 × 1023 molecules/mol), *M* is the molecular weight of water (18 g/mol), and ω is the water cross-section area (1.05 × 10−19 m2/molecule).

Sizes and volumes of capillaries of the examined material were determined for the area of capillary condensation using Kelvin’s equation, and assuming the cylindrical shape of the capillaries

\[
\ln a_{w} = \frac{2\sigma V}{\gamma_{c} RT} \tag{6}
\]

where σ is the surface tension of the liquid at temperature *T* (N/m), *γc* is the capillary radius (nm), *R* is the universal gas constant (kJ/mol·K), *T* is the process temperature (K), and *V* is the molar volume of the adsorbate (m3/mol).22,23

![AUTHOR INFORMATION](https://dx.doi.org/10.1021/acsomega.0c00851)

**Corresponding Author**

Malgorzata Zieba — Faculty of Chemical Engineering and Commodity Science, Department of Commodity Science and Quality Sciences, Radom University of Technology and Humanities, 26-600 Radom, Poland; orcid.org/0000-0003-2535-8300; Email: m.zieba@uthrad.pl

**Author**

Aneta Ocieczek — Faculty of Entrepreneurship and Quality Science, Department of Commodity Science and Quality Management, Gdynia Maritime University, 81-225 Gdynia, Poland; orcid.org/0000-0003-0173-4439

Complete contact information is available at:
Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The works are financed from funds of the Ministry of Science and Higher Education from the subsidy for statutory activities: Project no. WPiT/2019/PZ/05 entitled “Technical and natural aspects of products quality and consumer behaviors towards these products” (95% share in study costs) and Project no. 3086/35/P entitled “Development of recipes and technologies for the production of innovative cosmetics, pharmaceutical products, as well as household and industry chemicals” (5% share in study costs).

■ REFERENCES

(1) 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. Pol. J. Commod. Sci. Technologia. Jakos Przemysł. Ind. Eng. Chem. Process Des. Dev. 1975, 1938, 60, 384.
(2) Zięba, M.; Wieczorek, D.; Klimasewszka, E.; Malysa, A.; Kwasienniewska, D. Application of new synthesized zwitterionic surfactants as hair shampoo components. J. Dispersion Sci. Technol. 2018, 40, 1189–1196.
(3) Zięba, M.; Seweryn, A.; Klimasewszka, E.; Wieczorek, D. Reduction of hair shampoos irritant potential by application of zwitterionic surfactants. Przemysł Chemiczny 2019, 98, 581–585.
(4) Rahman, M. S. Food stability beyond water activity and glass transition: macro-micro region concept in the state diagram. Int. J. Food Prop. 2009, 12, 726–740.
(5) Spiess, W. E. L.; Wolf, W. Critical evaluation of methods to determine moisture sorption isotherms. In Water activity: theory and applications to food; Rockland, L. R.; Beuchat, L. R. (eds) Routledge: 2017, pp. 215–233.
(6) Chirife, J.; del Pilar Buera, M.; Labuza, T. P. Water activity, water glass dynamics, and the control of microbiological growth in foods. Crit. Rev. Food Sci. Nutr. 1996, 36, 465–513.
(7) Chirife, J.; del Buera, M. Water activity, glass transition and microbial stability in concentrated/semitmoist food systems. J. Food Sci. 1994, 59, 921–927.
(8) Paderewski, M. Process of adsorption in chemical engineering; WNT: Warszawa, 1999.
(9) Lowell, P. S.; Schwickel, K.; Parsons, T. B.; Sladek, K. J. Selection of metal oxides for removing SO2 from flue gas. Ind. Eng. Chem. Process Des. Dev. 1971, 10, 384.
(10) Dubinin, M. M. Adsorption and porosity; WNT: Warszawa, 1975.
(11) Rudabaszewa, S.P. Massopierenos w sistemach twiordoj fazoj; Moskwa: Chimija, 1977.
(12) Brunauer, S.; Emmett, P. H.; Teller, E. Adsorption of gases in multimolecular layers. J. Am. Chem. Soc. 1938, 60, 309–319.
(13) Karel, M. Water activity and food preservation. in Principles of food science; Ed. Karel, M.; Fennema, O. R.; Lund, D. B., Marcel Dekker: New York, 1976, pp. 237.
(14) Atkins, P. W. Physical Chemistry; Wydawnictwo Naukowe PWN: Warszawa, 2003.
(15) Lewicki, P. P. The applicability of the GAB model to food water sorption isotherms. Int. J. Food Sci. Technol. 1997, 32, 553–557.
(16) Diosady, L. L.; Rizvi, S. S. H.; Cai, W.; Jagdeo, D. J. Moisture sorption isotherms of canola meals and applications to packaging. J. Food Sci. 1996, 61, 204–208.
(17) Ocieczek, A.; Schur, J. Ocena wpływu wybranych dodatków na właściwości sorpcyjne miekisz wytrawionego pszennego. Żywność. Nauka. Technologia. Jakość 2015, 1, 143–154.
(18) Caurie, M. The derivation of the GAB adsorption equation from the BDDT adsorption theory. Int. J. Food Sci. Technol. 2006, 41, 173–179.
(19) Chirife, J.; Iglesias, H. A. Estimation of precision of isosteric heat of sorption determined from the temperature dependence of food isotherms. LWT–Food Sci. Technol. 1992, 25, 83–84.
(20) Andrade, R. D.; Lemus, M. R.; Pérez, C. C. E. Models of sorption isotherms for food: uses and limitations. Vitae 2011, 18, 325–334.
(21) Ocieczek, A.; Skotnicka, M.; Baranowska, K. Sorptive properties of modified maize starch as indicators of their quality. Int. Agrophys. 2017, 31, 383–392.
(22) Figura, L. O.; Teixeira, A. A. Food Physics. Physical Properties – Measurement and Applications; Springer-Verlag: Berlin Heidelberg, 2009.
(23) Palacha, Z.; Sitkiewicz, I. Physical properties of food; WNT: Warszawa, 2010.
(24) Ocieczek, A.; Kostek, R. Sorptive properties of type 2000 wheat and rye flours. Acta Agrophys. 2009, 14, 393–402.