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Research article

Modelling desorption isotherm for durable meat products

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HIGHLIGHTS

- A new Dynamic Dewpoint Isotherm and Saturated Salt Slurry method were compared.
- Technological solution for a new type of durable meat product was designed.
- A new Dynamic Dewpoint Isotherm was more accurate than Saturated Salt Slurry method.
- The new DLP model best fits for durable meat products than commonly used models.

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ABSTRACT

The desorption isotherms of two durable meat products (sample 1 - durable fermented meat product and sample 2 - unheated durable meat product) by Dynamic Dewpoint Isotherm (DDI) at 20, 25, and 30 °C and Saturated Salt Slurry (SSS) method at 20 °C has been studied. The data acquired from these measurements for 7 models (GAB, DLP, Henderson, Chin, Smith, Oswin, Halsey) were used and statistically evaluated. Based on our collected data, the most suitable model for these types of durable meat products is the DLP model. For the DDI method, DLP model (20–30 °C) reached the $R^2 = 0.999$, P value 3.48–4.22 of sample 1 and $R^2 = 0.999$, P value 1.51–3.24 of sample 2. For SSS method DLP model (20 °C) reached $R^2 = 0.999$, P value 4.23 of sample 1 and $R^2 = 0.998$, P value 3.68 of sample 2. The most commonly used GAB model according to statistical treatment was very accurate only for the DDI method, GAB model (20–30 °C) reached $R^2 \geq 0.994$, P value 1.93–7.12 of sample 1 and $R^2 = 0.999$, P value 1.76–5.54 of sample 2. In general, for DDI method for both samples have models (DLP, GAB, Halsey, Henderson, and Oswin) a P value of less than 10% for all three measured temperatures. For the SSS method, only the DLP and Henderson models are below 10% for both samples. It has been verified that the DDI method is a suitable and accurate method for measuring desorption isotherms for durable meat products.

1. Introduction

Meat products are regulated in Czech legislation by Decree No. 69/2016 Coll. on requirements for meat, meat products, fishery and aquaculture products, and products thereof, eggs, and products thereof, which, apart from the basic definitions, composition and sensory requirements, divides meat products into two main groups, meat products and semi-finished meat products. The meat products are further divided into seven subgroups: heat-treated, non-heat treated, non-heat treated for heat processing, long-life heat-treated, long-life fermented, cans, and semi-preserves. The drying, fermentation, aging, and smoking processes are used in three of the seven groups of meat products (Table 1) (Decree No. 69/2016 Coll., 2016). The production of durable meat products is very problematic. In particular, there is a strong focus on the hygiene requirements of the production areas and the microbial stability of the raw materials. Furthermore, the production process itself is costly and time–consuming (Leroy et al., 2006; Costa-Corredor et al., 2010; Astiasarán and Ansorena, 2016). Each of these products has its own specific legislative requirements and therefore specific requirements for technological operations. All product groups are classified as durable, and their microbial stability is ensured by a combination of several anabiotic interventions, which together create a barrier effect. The most important are the reduction of water activity and pH value or pasteurization/drying (Toldrá, 2004).

The water content is variable, with changes primarily occurring in production processes (e.g., drying, smoking, baking) aimed at reducing

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Table 1. Legislative parameters of durable meat products (Czech Republic).

Product	Processes	Water Activity	Storage Temperature	Names of Typical Products
Unheated durable meat product	Fermentation (optional), drying <70 °C	Not defined	0–2 °C*	Dried meat Prosciutto Bresaola
Durable heat-treated meat product	Pasteurization, drying	≤0.93	0–20 °C*	Vysočina salami, Brdská sausage Turistický salami
Durable fermented meat product	Fermentation, drying, maturing	≤0.93	0–20 °C*	Herkules Paprikáš Lovecký salami

*Data from labels of the manufactured products.

water activity and increasing shelf life (Berk, 2009; Nielsen, 2010; Schmidt and Lee, 2012). Water activity is the most important factor in terms of the chemical, biochemical, and microbial stability of food (Grandison and Brennan, 2011). The relationship between water activity and food water content at constant temperature and pressure is called a sorption isotherm (Aviara, 2020; Polatoğlu et al., 2011; Caballero-Cerón et al., 2015; Al-Muhtaseb et al., 2002; Mathlouthi and Rogé, 2003). There are several methods to determine sorption isotherms (hygroscopic, manometric), but the most commonly used method is the gravimetric method (Fontana and Carter, 2020).

The Saturated Salt Slurry method (SSS) is a standard method for the determination of sorption isotherms. The principle of the method is the ability of the material (food) to strike a balance with the environment. In a closed container (desiccator), a known relative humidity environment is created using various saturated salt solutions or differently concentrated sulfuric acid solutions. The samples are placed in desiccators with known relative humidity and left there to settle for several days to months at a constant temperature. A weight is determined gravimetrically (Schmidt and Lee, 2012; Lewicki and Pomaranska-Lazuka, 2003).

For the Dynamic Dewpoint Isotherm (DDI) method, water activity is directly measured using a humidifier with a cooled mirror and humidity is measured gravimetrically. The sample is first moistened with water-saturated air (adsorption) and then dried by air (desorption), which passes through a moisture-removing absorber before entering the measuring chamber. There is a small change in the water activity value ($\Delta a_w = 0.0015$) every time, the air flow is stopped and both, water activity and humidity, are measured (Schmidt and Lee, 2012; Fontana and Carter, 2020; Romani et al., 2016).

The aim of this study was to investigate the desorption isotherm of durable fermented meat product (sample 1) and unheated durable meat product (sample 2) by Dynamic Dewpoint Isotherm (DDI) method at 20, 25, and 30 °C and by the Saturated Salt Slurry (SSS) at 20 °C. Comparison of these two methods and recommendation of the most suitable model for these types of durable meat products were performed.

2. Materials and methods

2.1. Durable meat products manufacturing

The recipes of durable fermented meat product (sample 1) and unheated durable meat product 2 (sample 2) were the same. In 100 kg of product: pork shoulder (S2) 72.3 kg, frozen pork belly (S5) 24 kg (Landrace pig breed) (VÁHALA s.r.o., Czech Republic), 0.01 kg starter cultures of *Lactobacillus sakei*, *Pediococcus acidilactici*, and *Staphylococcus carnosus* (Chr. Hansen, Denmark), curing salt 1.9 kg, spice mixture I 1.39 kg (white pepper and black pepper, dextrose), aroma, glucose syrup, sodium ascorbate, spice extracts, spice mixture II 0.4 kg (pork protein, dried vegetables – beetroot) (TRUMF International Ltd., Czech Republic), and collagen casing 19/21 (Devro Ltd., Czech Republic).

Table 2. Settings of the smoking chamber for sample 1.

Time (h)	Temperature (°C)	Relative Humidity (%)	Process
6	26	85	Aging
18	26	92	Aging
1	24	–	Drying
0.2	25	–	Smoking
0.2	25	–	Drying
0.2	25	–	Smoking
2	24	88	Aging
2	22	88	Aging
2	20	85	Aging
0.2	25	–	Smoking
0.2	25	–	Drying
0.2	25	–	Smoking
48	18	82	Aging
72	16	80	Aging
360	24	78	Aging

The production took place in the company of Trumf Internacional Ltd. Frozen pork belly (−15 °C) was placed in a cutter (GEA, Germany) and was cut to a homogeneous mixture. After homogenization, fresh pork shoulder was added and minced to 5 mm size. Other ingredients were added: spices, starter cultures, and curing salt. During grinding, the temperature was controlled and did not exceed -2 °C. An automatic filler (VEMAG, Germany) was used to fill the mixture into edible collagen casing 19/21. A filled products were mounted on trolleys and left to dry for 12 h. This was followed by fermentation and drying in an air-conditioned smoking and aging chamber (Mauting s.r.o., Czech Republic). For the process and settings of the smoking chamber for sample 1, see Table 2. Production of the unheated meat product (sample 2) involved the following steps: *i)* heat treatment of the product in an air-conditioned chamber (65 °C) until the core temperature of the products reached 55 °C, *ii)* 10 min of drying, *iii)* 10 min off smoking, and *iv)* 2 min off drying. All processes were performed at 55 °C. The initial weight of the two types of salami was 300 g and samples were stored in refrigerator at temperature 4.0 ± 0.5 °C before the evaluation.

2.2. Physico-chemical analyzes

The dry matter, water activity, and pH value of both samples were determined. For the first sample, the input mixture was analyzed and then samples were taken for analysis day No. 1, 2, 5, 9, 12, 15, 19, and 21 of the aging process. For sample 2, only the final product was analyzed. The water content of the samples was determined by drying at 103 ± 2 °C in an oven HS 32 A (ZPA, Czech Republic) to a constant weight loss. (AOAC, 1980). The water activity was measured in triplicate with a_w meter Aqualab 4 TEV (Decagon Devices, USA) at a temperature of 25 °C. The pH determination was measured in triplicate using a Portavo 904 X pH meter (KNICK, Germany).

2.3. Moisture desorption analysis

For the determination of desorption isotherms, two methods were chosen: *i)* DDI (i.e., Dynamic Dewpoint Isotherm) and *ii)* SSS (i.e., Saturated Salt Slurry). The AquaLab Vapor Sorption Analyzer instrument (Decagon Devices, USA) was used for the DDI method and both samples were measured at different temperatures (20, 25, and 30 °C) and within the range of water activity from 0.97 to 0.50 (resolution 0.005).

The SSS method was used for the final products of the samples at a temperature of 20 °C. Saturated salt solutions were prepared from magnesium chloride hexahydrate p.a. (min. 99%) (a_w = 0.342),

Table 3. Selected sorption models.

Model	Mathematical expression	Equation
Halsey (Halsey, 1948)	$M = -\left(\frac{A}{\ln a_w}\right)^{\frac{1}{B}}$	(1)
Henderson (Henderson, 1952)	$M = \left[\frac{\ln(1-a_w)}{-A}\right]^{\frac{1}{B}}$	(2)
Smith (Smith, 1947)	$M = A - B\ln(1-a_w)$	(3)
DLP (Condon, 2006)	$M = A + B\cdot x + C\cdot x^2 + D\cdot x^3$	(4)
Chin (Boquet et al., 1978)	$M = \frac{A}{\ln a_w} + B$	(5)
Oswin (Oswin, 1946)	$M = A\left(\frac{a_w}{1-a_w}\right)^B$	(6)
GAB (Guggenheim, 1966; Anderson, 1946; de Boer, 1953)	$\frac{M}{M_m} = \frac{ABa_w}{(1-Ba_w)(1-Ba_w+ABa_w)}$	(7)

Key: M is equilibrium moisture content (g H_2O/100 g dry basis); a_w is water activity; M_m is monolayer moisture content (g H_2O/100 g dry basis); A, B, C, D are constants; x = ln[-ln(aw)].

potassium carbonate p.a. (min. 99%) ($a_w = 0.451$), sodium nitrite p.a. (min. 99%) ($a_w = 0.601$), sodium chloride p.a. (min. 99.9%) ($a_w = 0.762$), potassium chloride p.a. (min. 99.5%) ($a_w = 0.859$), and potassium nitrate p.a. (min. 99%) ($a_w = 0.944$) (PENTA s.r.o., Czech Republic). Desiccators were left for 50 days to stabilize the relative humidity. Microbial spoilage of the samples was prevented by the addition of 20 ml of toluene p.a. (min. 99%) (PENTA s.r.o., Czech Republic). The samples were measured in three parallel determinations and the change in moisture of the samples was detected gravimetrically.

2.4. Mathematical modelling of desorption data

The experimental data from the desorption isotherms were applied to the following seven sorption models: GAB (Guggenheim-Anderson-de Boer), DLP (Double Log Polynomial), Henderson, Chin, Smith, Oswin, and Halsey. The Eqs. (1), (2), (3), (4), (5), (6), and (7) are given in Table 3. Our measured data were compared with selected sorption isotherm models using regression analysis of linearized model equations in MATLAB R2019b software (MathWorks, USA). The moisture content in the isotherms was expressed as g H_2O/100 g dry basis (% d.b.).

Figure 1. Illustration of final salami products 1A (Sample 1) and 1B (Sample 2).

Table 4. Model parameters and statistical parameters for the desorption isotherm of sample 1 (final product) measured by the DDI method.

t (°C)	Model	Constants							
		A	B	C	D	M_m	R^2	RMSE	P (%)
20	Halsey	1.452	0.670	-	-	-	0.936	0.2741	4.01
	Chin	-4.933	-2.278	-	-	-	0.974	3.7913	33.83
	Henderson	0.002	0.384	-	-	-	0.989	0.1158	1.80
	Oswin	2.998	1.297	-	-	-	0.954	0.2317	3.35
	Smith	-30.255	35.919	-	-	-	0.960	4.6751	54.26
	GAB	0.049	0.909	-	-	50.325	0.998	0.9499	7.12
	DLP	2.039	4.002	12.411	0.451	-	0.999	0.4364	4.22
25	Halsey	1.183	1.340	-	-	-	0.983	0.1060	0.69
	Chin	-5.348	-0.621	-	-	-	0.980	3.1137	13.24
	Henderson	0.001	0.492	-	-	-	0.999	0.0293	0.18
	Oswin	5.476	1.046	-	-	-	0.992	0.0735	0.45
	Smith	-26.466	35.472	-	-	-	0.954	4.7085	29.37
	GAB	0.224	0.938	-	-	15.645	0.999	0.4480	1.93
	DLP	6.172	6.201	13.420	0.475	-	0.999	0.6929	3.48
30	Halsey	1.831	-0.381	-	-	-	0.914	0.3578	8.01
	Chin	-5.004	-7.839	-	-	-	0.990	2.3243	23.83
	Henderson	0.003	0.276	-	-	-	0.969	0.2132	4.88
	Oswin	1.084	1.673	-	-	-	0.929	0.3247	7.23
	Smith	-43.431	39.138	-	-	-	0.950	5.1802	84.08
	GAB	0.022	0.941	-	-	58.872	0.994	1.7579	2.65
	DLP	2.291	9.945	11.652	-0.390	-	0.999	0.5159	4.22

2.5. Statistical analysis

The statistical suitability of the individual models was expressed by the coefficient of determination (R^2), Root Mean Squared Error (RMSE), and mean relative percentage deviation (P), see Eqs. (8), (9), and (10) below. The model is considered acceptable if the P values are below 10% (Delgado and Sun, 2002a; Jena and Das, 2012). All data were processed in MATLAB R2019b software (MathWorks, USA).

$$R^2 = 1 - \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \tag{8}$$

$$RMSE = \sqrt{\frac{\sum(\hat{y}_i - \bar{y})^2}{n}} \tag{9}$$

$$P\ (\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i} \tag{10}$$

Where y_i is experimental moisture content, $\hat{y}_i$ is predicted moisture content, n the number of observations, $\bar{y}$ is mean value of experimental moisture content.

3. Results and discussion

3.1. Durable meat products manufacturing

Two types of salami using the same recipe differing in production technologies were produced. Sample 1 was dried for 21 days and, according to Czech legislation, it is classified as a durable fermented meat product. Sample 2 was heat-treated at 55 °C and briefly dried; ranked in the group of unheated durable meat products. Production of sample 1 is

Table 5. Model parameters and statistical parameters for the desorption isotherm of sample 2 (final product) measured by the DDI method.

t (°C)	Model	Constants							
		A	B	C	D	M_m	R^2	RMSE	P (%)
20	Halsey	1.052	1.471	-	-	-	0.976	0.1311	0.82
	Chin	-4.071	3.408	-	-	-	0.964	4.6040	22.58
	Henderson	0.001	0.520	-	-	-	0.999	0.0276	0.16
	Oswin	5.920	0.944	-	-	-	0.986	0.0980	0.58
	Smith	-25.320	33.968	-	-	-	0.965	4.5314	27.55
	GAB	0.363	0.945	-	-	11.141	0.999	0.5605	1.78
	DLP	6.072	5.193	12.851	0.824	-	0.999	0.7809	3.20
25	Halsey	0.693	2.344	-	-	-	0.999	0.0206	0.03
	Chin	-3.442	12.171	-	-	-	0.977	3.6560	10.13
	Henderson	0.000	0.787	-	-	-	0.975	0.0942	0.33
	Oswin	12.782	0.621	-	-	-	0.998	0.0263	0.09
	Smith	-14.548	30.763	-	-	-	0.959	4.8766	15.74
	GAB	0.000	0.787	-	-	6.782	0.999	0.8010	1.76
	DLP	13.199	0.206	7.160	-0.209	-	0.999	0.8630	1.51
30	Halsey	1.215	1.077	-	-	-	0.963	0.1855	1.87
	Chin	-4.433	-0.154	-	-	-	0.983	3.3290	22.46
	Henderson	0.001	0.448	-	-	-	0.998	0.0448	0.50
	Oswin	4.179	1.092	-	-	-	0.977	0.1469	1.46
	Smith	-29.404	35.550	-	-	-	0.952	5.5674	43.89
	GAB	0.001	0.448	-	-	11.491	0.999	0.5533	5.54
	DLP	1.877	-1.676	6.629	-0.751	-	0.999	0.6446	3.24

Table 6. Model parameters and statistical parameters for the desorption isotherm of sample 1 and sample 2 measured by the SSS method at 20 °C.

Sample	Model	Constants							
		A	B	C	D	M_m	R^2	RMSE	P (%)
1	Halsey	343.606	0.638	-	-	-	0.922	0.4571	15.50
	Chin	-3.745	0.255	-	-	-	0.956	4.6196	132.22
	Henderson	0.002	0.410	-	-	-	0.985	0.1996	7.06
	Oswin	2.270	1.343	-	-	-	0.949	0.3684	10.98
	Smith	-14.773	25.459	-	-	-	0.978	3.2604	132.28
	GAB	0.002	0.410	-	-	99.007	0.995	1.5125	66.62
	DLP	0.661	1.294	13.750	2.026	-	0.999	0.1234	4.23
2	Halsey	0.667	2.459	-	-	-	0.979	0.0981	0.54
	Chin	-3.653	12.084	-	-	-	0.960	4.2566	19.20
	Henderson	0.0002	0.994	-	-	-	0.986	0.0787	0.23
	Oswin	15.136	0.566	-	-	-	0.990	0.0663	0.38
	Smith	-2.551	24.816	-	-	-	0.981	2.9301	10.28
	GAB	10.631	0.931	-	-	8.878	0.997	1.1234	6.08
	DLP	10.871	-13.371	-0.655	-1.248	-	0.998	0.8931	3.68

faster compared to sample 2. These are hours of process, not days. In addition, there is no need for the aging process in a special air-conditioned chamber. Due to the shorter production time and energy consumption, the cost of the overall production process of this fermented product is also lower. The final products of durable meat products are shown in Figures 1A and 1B.

3.2. Physico-chemical analyzes

The initial water content of sample 1 was 60.3 ± 0.8 g/100 g total. After 21 days of drying, the water content was 30.7 ± 1.7 g/100 g total. That means that water loss was around 30%. Sample 2 contained 49.1 ± 0.8 g/100 g total. Water loss was around 10%. A Similar trend can be

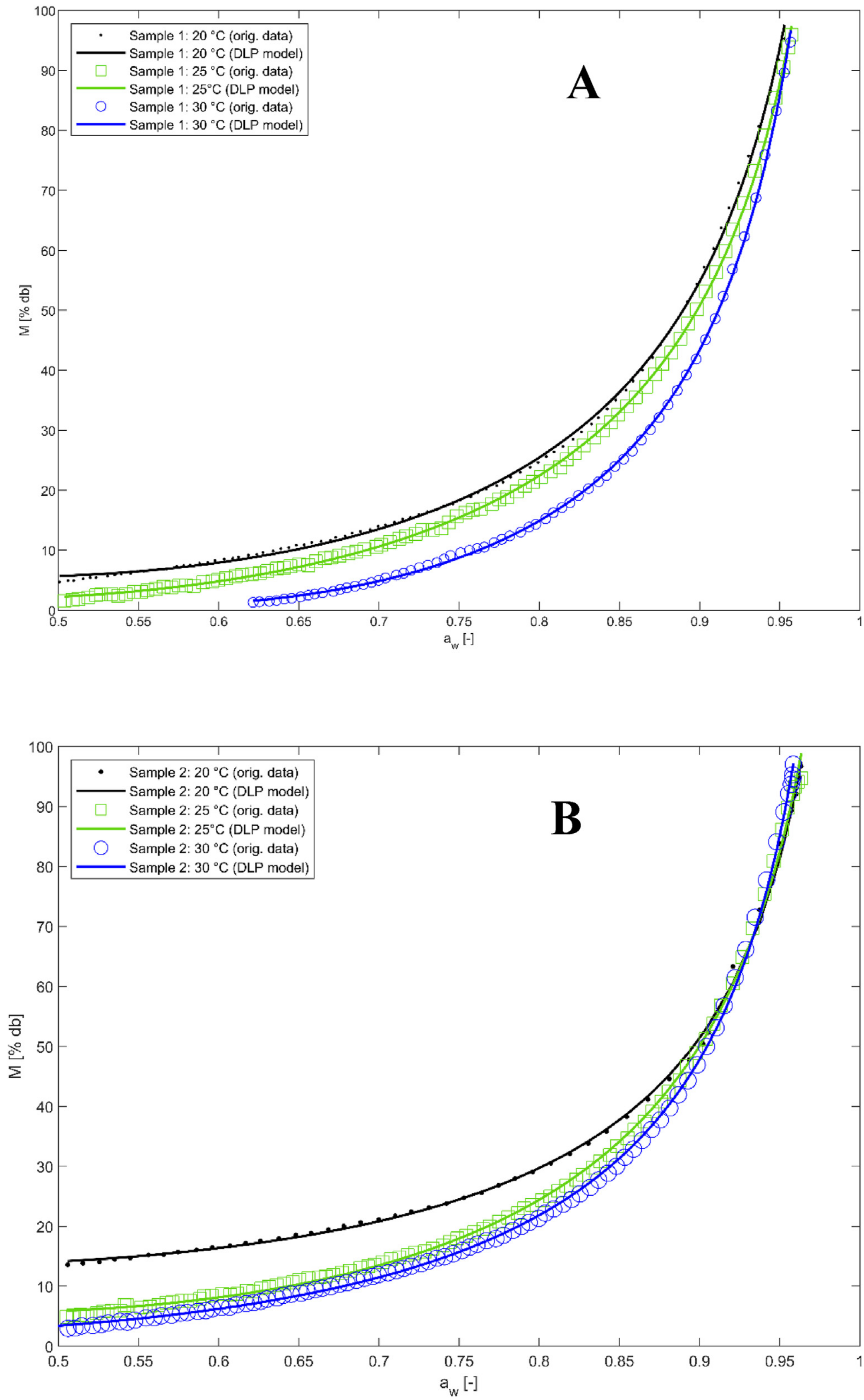

Figure 2. Experimental DDI moisture desorption isotherm and DLP model at 20 °C, 25 °C, 30 °C for sample 1 (A) and sample 2 (B).

seen in the study Ščetar et al. (2013). The initial water activity value was 0.981 ± 0.001. On day 12, water activity was 0.931 ± 0.003. After 12 days, the product reached the value $a_w = 0.930$ to be considered a durable fermented meat product according to Decree No. 69/2016 Coll. The final water activity was 0.887 ± 0.001. For sample 2, the measured water activity was 0.970 ± 0.001. For sample 1 during the first nine days, the pH value decreased from 6.05 ± 0.03 to 4.73 ± 0.01 due to the starter culture producing lactic acid. The following days showed a slight

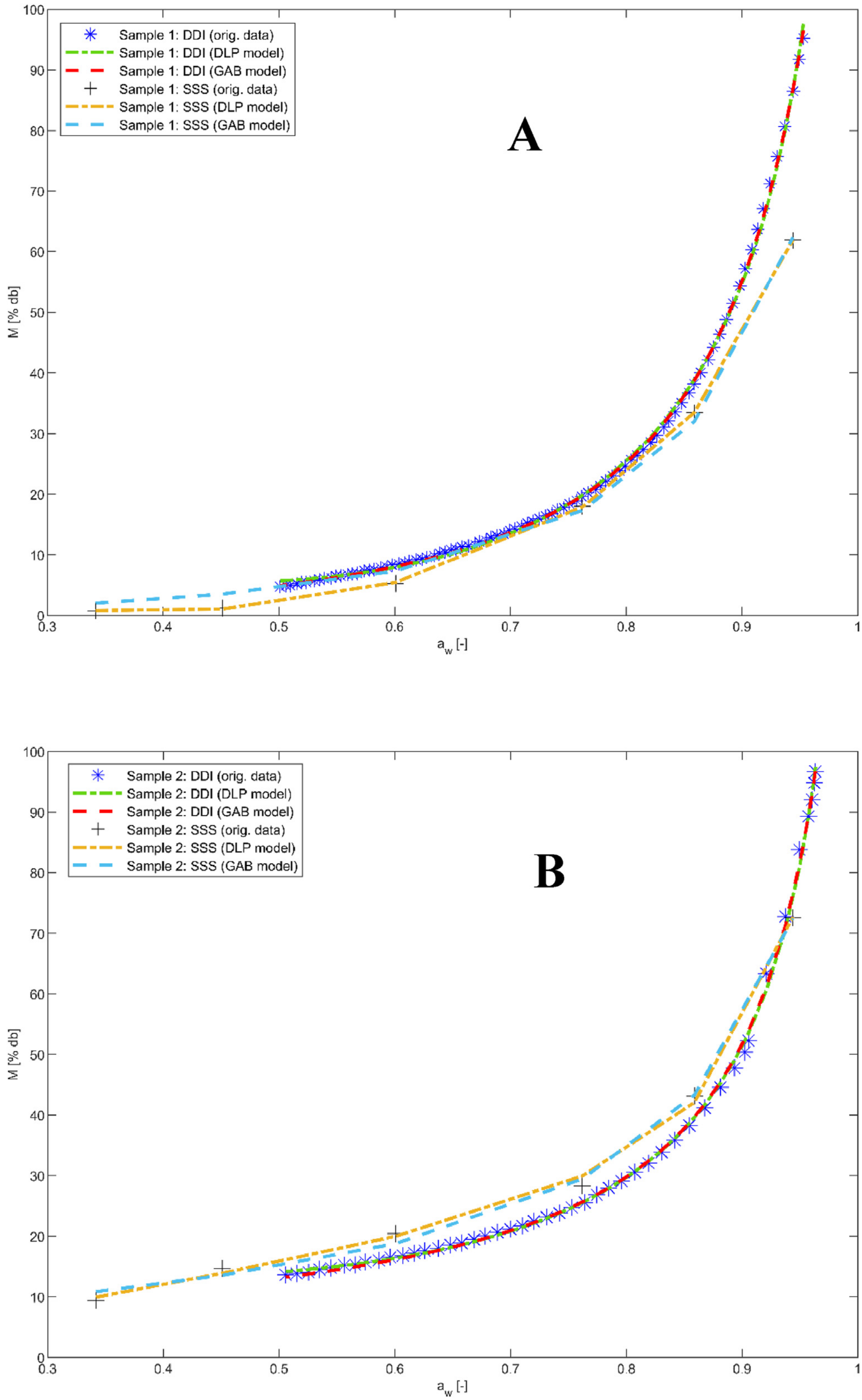

Figure 3. Comparison of the experimental DDI and SSS moisture desorption isotherm with the DLP model at 20 °C for sample 1 (A) and sample 2 (B).

increase in pH (to a final value of 4.80 ± 0.01) due, among other things, to the buffering activity of proteins. The pH value of sample 2 was 5.34 ± 0.04. A Similar trend can be seen in the study Marcos et al. (2020).

3.3. Moisture desorption analysis

The DDI method was used to measure the desorption isotherms of final samples 1 and 2 within the water activity range of 0.95–0.50 with a resolution of 0.005 for three different temperatures (20, 25, and 30 °C). In total, 90 values were recorded for each measurement using this method, except for sample 1 at 30 °C, where water activity of 0.65 resulted in poor water desorption and 70 values were measured. The DDI method recorded a total of 520 values processed in MATLAB R2019b for 7 different models of sorption isotherms (GAB, DLP, Henderson, Chin, Smith, Oswin, Halsey) whose resulting constant values together with coefficient determination (R^2), Root Mean Square Error (RMSE), and relative percentage deviation (P) are given in Table 4 and Table 5.

The SSS standard method measured both final samples at 20 °C. Saturated solutions and their actual water activity are given in Section 2.3. The stabilization of relative humidity lasted for 50 days and then changes in humidity were detected gravimetrically. The measured data were evaluated in MATLAB R2019b with the same models and parameters as the DDI method. Model parameters and statistical parameters for the desorption isotherm of fermented meat products measured by the SSS method are given in Table 6.

Figures 2A and 2B show the desorption isotherms measured by the DDI method for temperatures of 20, 25, and 30 °C and spacing with the DLP model, which appears to be the most accurate of all models. Figure 3 compares the DDI and SSS methods for sample 1 (Figure 3A) and sample 2 (Figure 3B), and the measured data in the graphs are interspersed with the DLP and GAB models.

There are very few publications in which sorption isotherms are measured with high accuracy (Aykin-Dinçer and Erbaş, 2018; Muñoz et al., 2009) and there are also missing data of sorption isotherms (desorption, adsorption) measured using the DDI method for meat products. Sorption isotherms, created using the DDI method, exist only for certain types of products – for example biscuits and starch (Marques et al., 2020; Romani et al., 2016). The standard method using saturated solutions is mostly used for the formation of sorption isotherms of meat products. Only a few isothermal points are recorded during this method (Ndob and Lebert, 2018; Ahmat et al., 2014).

According to Jena and Das (2012) the DDI model is generally accepted if P is less than 10%. Apart from the models of Smith and Chin, which are completely unsuitable for modelling these meat products isotherms for both methods used, the other models (DLP, GAB, Halsey, Henderson, and Oswin) for the DDI method have a P value of less than 10% for all three measured temperatures. Compared with the SSS model, only the DLP and Henderson models are below 10%, Oswin model is just above 10% by sample 1. It is because of the lower values by first and last point. By sample 2 compared SSS method with DDI method was very accurate. The DLP model is the most appropriate for assessing sorption isotherms of durable meat products, R^2 value ≥0.998, RMSE ≤0.8931, and P value ≤4.23. The most used GAB model, by statistical treatment, was very accurate for the DDI method, vice versa the SSS method, where P ≥ 6.08, with the exception of the SSS method for sample 1. Another suitable model is the Henderson model, for the DDI model it reached R^2 ≥ 0.969, RMSE ≤0.2132, and P value ≤4.88, and for the SSS model it reached R^2 ≥ 0.985, RMSE ≤0.1996, and P value ≤7.06. Other suitable models for both methods are the Halsey and Oswin models.

Compared to some studies (Muñoz et al., 2009; Kabil et al., 2012), where desorption isotherms were measured for similar matrices but only by the standard method, the R^2 and P values were very similar. The DDI method, compared with study Romani et al. (2016), is much more accurate. The P value is less than 10% compared with study Marques et al. (2020) by DDI method. Whereas in the literature, the P values are higher (Kabil et al., 2012), meaning a high degree of precision of our values. This implies that the DDI method can achieve significantly more accurate sorption isolate modelling, which could also be used in practice.

Figures 2A and 2B compare the desorption isotherms for three different temperatures (20 °C, 25 °C, 30 °C) by the DDI method and shows the experimental points vs. the predicted isotherm (samples 1 and 2). These temperatures are chosen because of the range most used in smoking chamber processes and can be used to optimize smoking, drying, and aging processes. As expected in this work for these types of meat products at the same water content, the water activity increases with increasing temperature. This can be explained by the fact that temperature affects the mobility of water molecules and the dynamic balance between the water vapor and adsorbed phases. Similar results have been reported Delgado and Sun (2002b). The DLP model was selected in the graph due to the most accurate model and best fits to the measured data. The DLP model is a very accurate model for predicting desorption isotherms for durable meat products. Similar results of DLP model, but for different matrix, have been reported in study Lin and Nurtama (2010). The differences between the individual samples, which used different production technologies for the desorption isotherms measured by the DDI method at three temperatures, are not evident because of the same matrix used.

The comparison between the two methods, the standard SSS method and the new DDI method, used in this work shows Figures 3A and 3B. These graphs compare the DDI and SSS methods at 20 °C with the DLP and GAB models, which were selected from the statistics as the most suitable models for these two methods, and it can be seen in the graphs that fitting these models to the measured date is very accurate.

The advantages of the DDI method are mainly its speed (each sample was measured for 12 h) compared to the SSS method (all samples were measured for 50 days). Furthermore, at higher values of water activity, there is no microbiological destruction of the samples. Other advantage is fast sample preparation and faster measurement speed instead of the gravimetric tip in the SSS method. Despite only seven measured points compared to the 70 points of the DDI desorption method, the SSS method is also a very accurate measurement method for certain types of models according to statistical data.

4. Conclusion

The most suitable model for these types of durable meat products is the DLP model, in which the R^2 for both methods was ≥0.998, RMSE ≤0.8931 and the P value ≤4.23. The most commonly used GAB model according to statistical processing was very accurate for the DDI method, in contrast to the SSS method, where its P values are higher than 6.08. Another suitable model is the Henderson model, which reached R^2 ≥ 0.969, RMSE ≤0.2132 and P value ≤4.88 for the DDI method and R^2 ≥ 0.985, RMSE ≤0.1996 and P value ≤7.06 for the SSS method. In general, except for the Smith and Chin models, which are completely unsuitable for modelling these types of meat products with both methods used, the other models (DLP, GAB, Halsey, Henderson, and Oswin) have a P value of less than 10% for all three measured temperatures within DDI. Unlike the SSS method, only the DLP and Henderson models are below 10% for both samples. It follows that the DDI method can achieve significantly more accurate modelling of sorption isotherms, which can be used in practice well.

Declarations

Author contribution statement

Josef Bauer: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Přemysl Richtr: Performed the experiments, Analyzed and interpreted the data, Wrote the paper.

Filip Beňo; Adam Tobolka: Performed the experiments; Wrote the paper

Rudolf Ševčík: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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