Modelling desorption isotherm for durable meat products

Josef Bauer, Premysl Richter, Filip Beno, Adam Tobolka, Rudolf Ševčík

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.

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.

ARTICLE INFO

Keywords:
DDI method
SSS method
Desorption isotherm
Durable meat products
Sorption isotherm models

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 R² = 0.999, P value 3.48–4.22 of sample 1 and R² = 0.999, P value 1.51–3.24 of sample 2. For SSS method DLP model (20 °C) reached R² = 0.999, P value 4.23 of sample 1 and R² = 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 R² = 0.994, P value 1.93–7.12 of sample 1 and R² = 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...
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; Polatoglu et al., 2011; Caballerero-Cerón et al., 2015; Al-Muhtaseb et al., 2002; Mathlouthi and Rogé, 2003). There are several methods to determine sorption isotherms (hygrosopic, 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 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 (Δaw = 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; Romaní 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 (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) (VAHILA 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 11.39 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).

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 aw 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%) (aw = 0.342),

### 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 | Not defined | 0–2 °C* | Dried meat Prosciutto Bresaola |
| Durable heat-treated meat product | Pasteurization, drying | ≤0.93 | 0–20 °C* | Vysocina salami, Brdka sausage, Touristiky salami |
| Durable fermented meat product | Fermentation, drying, maturing | ≤0.93 | 0–20 °C* | Herkules Paprikas, Lovecký salami |

*Data from labels of the manufactured products.

### 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   |
potassium carbonate p.a. (min. 99%) (aw = 0.451), sodium nitrite p.a. (min. 99%) (aw = 0.601), sodium chloride p.a. (min. 99.9%) (aw = 0.762), potassium chloride p.a. (min. 99.5%) (aw = 0.859), and potassium nitrate p.a. (min. 99%) (aw = 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 H2O/100 g dry basis (% d.b.).

Table 3. Selected sorption models.

| Model          | Mathematical expression | Equation |
|----------------|-------------------------|----------|
| Halsey (Halsey, 1948) | $M = \left( \frac{A}{M_m} \right)^{\frac{1}{B}}$ | (1)      |
| Henderson (Henderson, 1952) | $M = \frac{\ln(1 - \alpha_w)}{-A}$ | (2)      |
| Smith (Smith, 1947) | $M = A - B \ln(1 - \alpha_w)$ | (3)      |
| Chin (Boquet et al., 1978) | $M = \frac{A}{\alpha_w} + B$ | (5)      |
| Oswin (Oswin, 1946) | $M = A \left( \frac{\alpha_w}{1 - \alpha_w} \right)^{s}$ | (6)      |
| GAB (Guggenheim, 1966; Anderson, 1946; de Boer, 1953) | $M = M_m - \frac{AB\alpha_w(1 - \alpha_w)}{(1 - B\alpha_w)(1 - B\alpha_w + AB\alpha_w)}$ | (7)      |

Key: M is equilibrium moisture content (g H2O/100 g dry basis); aw is water activity; Mm is monolayer moisture content (g H2O/100 g dry basis); A, B, C, D are constants; x = ln[-ln(aw)].

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 | Mm | R² | 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 |
|       | Smith | 2.998     | 1.297 | - | - | - | 0.954 | 0.2317 | 3.35 |
|       | Oswin | 30.255   | 35.919 | - | - | - | 0.960 | 4.6751 | 54.26 |
|       | GAB   | 2.039   | 4.002 | 12.411 | 0.451 | - | 0.998 | 0.9499 | 7.12 |
| 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 |
|       | Smith  | 5.476    | 1.046 | - | - | - | 0.992 | 0.0735 | 0.45 |
|       | Oswin | 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 |
|       | Smith  | 1.084    | 1.673 | - | - | - | 0.929 | 0.3247 | 7.22 |
|       | Oswin | -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).

\begin{equation}
R^2 = 1 - \frac{\sum (\hat{y}_i - \bar{y})^2}{\sum (y_i - \bar{y})^2}
\end{equation}

\begin{equation}
RMSE = \sqrt{\frac{\sum (\hat{y}_i - \bar{y})^2}{n}}
\end{equation}

\begin{equation}
P(\%) = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{y_i - \hat{y}_i}{\bar{y}_i} \right|
\end{equation}

Where $y_i$ is experimental moisture content, $\hat{y}_i$ is predicted moisture content, $n$ the number of observations, and $\bar{y}$ 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 \degree C and briefly dried; ranked in the group of unheated durable meat products. Production of sample 1 is

| t (\degree C) | Model | A | B | C | D | $M_n$ | $R^2$ | 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| -| -| -| 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| -| -| -| 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| -| -| -| 0.999| 0.5533| 5.54 |
|              | DLP   | 1.877| -1.676| 6.629| -0.751| -| 0.999| 0.6446| 3.24 |

| Sample | Model | A | B | C | D | $M_n$ | $R^2$ | 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| -| -| -| 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 $60.3 \pm 0.8 \text{g/100 g total}$. After 21 days of drying, the water content was $30.7 \pm 1.7 \text{g/100 g total}$. That means that water loss was around 30%. Sample 2 contained $49.1 \pm 0.8 \text{ g/100 g total}$. Water loss was around 10%. A Similar trend can be

Figure 2. Experimental DDI moisture desorption isotherm and DLP model at $20 \degree \text{C}, 25 \degree \text{C}, 30 \degree \text{C}$ for sample 1 (A) and sample 2 (B).
seen in the study Šćetar 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 decrease.
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 DLP model is a very accurate model for predicting desorption isotherms of durable meat products, which can be used in practice.

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.

Piemysl Richter: Performed the experiments, Analyzed and interpreted the data, Wrote the paper.
Filip Beno; Adam Tobolka: Performed the experiments; Wrote the paper  
Rudolf Ševčík: Contributed reagents, materials, analysis tools or data;  
Wrote the paper.

Funding statement

Ing. Josef Bauer was supported by University of Chemistry and Technology in Prague [A2_FPBT_2020_051, A2_FPBT_2022_048, A1_FPBT_2022_003].

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.

References

Ahmat, T., Brunneau, D., Kuitche, A., Aregba, A.W., 2014. Desorption isotherms for fresh beef: an experimental and modeling approach. Meat Sci. 96, 1417–1424.  
Al-Muhtaseb, A.H., McMinn, W.A.M., Magee, T.R.A., 2002. Moisture sorption isotherm characteristics of food products: a review. Food Bioprod. Process. 80 (2), 118–126.  
Anderson, R.B., 1946. Modification of the BET equation. J. Am. Chem. Soc. 68, 686–691.  
AOAC, 1980. Ofﬁcial Methods of Analysis, thirteenth ed. Association of Ofﬁcial Analytical Chemists, Washington, DC, pp. 376–384.  
Ansisanz, Í., Ansorena, D., 2016. Sausages and Comminuted Products: Dry Fermented Products. Encyclopaedia of Food and Health, Aviara, N.A., 2020. Moisture Sorption Isotherms and Isotherm Model Performance Evaluation for Food and Agricultural Products. TechOpen, Ayken-Dincer, E., Erbog, M., 2018. Drying kinetics, adsorption isotherms and quality characteristics of vacuum-dried beef slices with different salt contents. Meat Sci. 145, 114–120.  
Berk, Z., 2005. Food Process Engineering and Technology. Elsevier/Academic Press.  
Boquet, R., Chirife, J., Iglesias, H.A., 1978. Equations for ﬁtting water sorption isotherms of food. Part II. Evaluation of various two-parameter models. J. Food Technol. 13, 319–328.  
Caballero-Cerín, C., Guerrero-Beltrán, J.A., Mújica-Paz, H., Torres, J.A., Welzi-Chanes, J., 2015. Moisture sorption isotherms of foods: experimental methodology, mathematical analysis, and practical applications. In: Gutiérrez-López, G.F., Alamilla-Beltrán, L., del Pilar Bueña, M., Welzi-Chanes, J., Parada-Arias, E., Barbosa-Cánovas, G.V. (Eds.), Water Stress in Biological, Chemical, Pharmaceutical and Food Systems. Springer, New York, pp. 187–214.  
Condon, J.B., 2006. Surface Area and Porosity Determinations by Physisorption: Measurements and Theory. Elsevier, Amsterdam.  
Costa-Corredor, A., Pakowski, Z., Lenczewski, T., Gou, P., 2010. Simulation of simultaneous water and salt diffusion in dry fermented sausages by the Stefan-Maxwell equation. J. Food Eng. 97 (3), 311–318.  
de Boer, J.H., 1953. The Dynamical Character of Adsorption. Clarendon Press, Oxford, UK.  
Delgado, A.E., Sun, D.W., 2002a. Desorption isotherms for cooked and cured beef and pork. J. Food Eng. 51, 163–170.  
Delgado, A.E., Sun, D.W., 2002b. Desorption isotherms and glass transition temperature for chicken meat. J. Food Eng. 55, 1–8.  
Fontana, A.J., Carter, B.P., 2020. Measurement of water activity, moisture sorption isotherm, and moisture content of foods, pp. 207–226. Barbosa-Cánovas, V., Fontana Jr., A.J., Schmidt, S.J., Labuza T.P. (Eds.), Water Activity in Foods.  
Grandison, A., Brennan, J.G., 2011. Food Processing Handbook, second ed.1 Guggenheim, E.A., 1966. Application of Statistical Mechanics. Clarendon Press, Oxford, UK.  
Halsey, G., 1948. Physical adsorption on non-uniform surfaces. J. Chem. Phys. 16, 931–937.  
Henderson, S.M., 1952. A basic concept of equilibrium moisture content. Agric. Eng. 33 (2), 931–937.  
Jena, S., Das, H., 2012. Moisture sorption studies on vacuum dried coconut presscakke. J. Food Sci. Technol. 49 (5), 638–642.  
Kalb, E., Aktas, N., Balci, E., 2012. Effect of sodium chloride, sodium nitrate and temperature on desorption isotherms of previously frozen beef. Meat Sci. 90, 932–938.  
Leroy, F., Verduyn, J., De Vuyts, L., 2006. Functional meat starter cultures for improved sausage fermentation. Int. J. Food Microbiol. 106 (3), 270–285.  
Lewicki, P.P., Pomaranska-Lazuk, W., 2003. Errors in static desiccator method of water sorption isotherms estimation. Int. J. Food Prop. 6 (3), 557–563.  
Lin, J., Nurtama, B., 2010. Moisture sorption isotherm characteristics of taro flour. World J. Dairy Food Sci. 5 (1), 1–6.  
Marcos, B., Gou, P., Arnau, J., Dolors Guix, M., Comaposada, J., 2020. Co-extruded alginate as an alternative to collagen casings in the production of dry-fermented sausages: impact of coating composition. Meat Sci. 169, 108–184.  
Marques, R.C.D., Oliveira, E.R., Coutinho, G.S.M., Ribeiro, A.E. Ch., Teixeira, C.S., Soares Júnior, M., Callaci, M., 2020. Modeling sorption properties of maize by-products obtained using the Dynamic Dewpoint Isotherm (DDI) method. Food Biosci. 38, 725–738.  
Mathlouthi, M., Régis, B., 2003. Water vapour sorption isotherms and the cooking of food powders. Food Chem. 82 (1), 61–71.  
Muñoz, J., Arnau, J., Costa-Corredor, A., Gou, P., 2009. Desorption isotherms of salted minced pork using K-lactate as a substitute for NaCl. Meat Sci. 83 (4), 642–646.  
Ndob, A.M., Lebert, A., 2018. Prediction of pH and aw of pork meat by a thermodynamic model: new developments. Meat Sci. 138, 59–67.  
Nielsen, S.S., 2010. Food Analysis Laboratory Manual. Springer US, Decree No. 69/2016 Coll., 2016. Czech republic, 2016. Decree on requirements for meat, meat product, ﬁshery and aquaculture products and products thereof, eggs and products thereof; Ministry of Agriculture: Prague, Czech Republic. Collection of laws Czech Republic 26, 714–759. Also available at: http://www.eagri.cz/public/web/mze/[2021-09-11].  
Oswin, C.R., 1946. The kinetics of package life. III. Th. isotherm. J. Chem. Ind. 65, 419–421, London.  
Polatoglou, B., Beşe, A.V., Kaya, M., Aktas, N., 2011. Moisture adsorption isotherms and thermodynamics properties of sucuk (Turkish dry-fermented sausage). Food Bioprod. Process. 89 (4), 449–456.  
Romani, S., Rocculi, P., Tappi, S., Dalla Rosa, M., 2016. Moisture adsorption behaviour of biscuit during storage investigated by using a new Dynamic Dewpoint method. Food Bioprod. 98 (4), 226–236.  
Scetar, M., Kovacić, E., Kurek, M., Galic, K., 2013. Shelf life of packaged sliced dry fermented sausage under different temperature. Meat Sci. 93, 802–809.  
Schmitt, S.J., Lee, J.W., 2012. Comparison between water vapor sorption isotherms obtained using the new Dynamic Dewpoint isotherm method and those obtained using the standard saturated salt Slurry method. Int. J. Food Prop. 15 (2), 236–248.  
Smith, S.E., 1947. The sorption of water vapour by high polymers. J. Am. Chem. Soc. 69, 646–651.  
Toldrá, F., 2004. Dry-cured Meat Products. Food & Nutrition Press.