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EXPERIMENTAL STUDY OF POLISH SAUSAGE DRYING KINETICS AND CONTRACTION BY IMAGE DATA ANALYSIS

– Research paper –

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Abstract: The goal of this paper has been to add an experimental data set for drying a meat product and provide a comparison with well-established thin-layer drying models. This article presented experimental investigations on the convective drying of Polish sausage slices at a temperature of 40ºC. Slices have been in the thickness of 3 to 8mm. Measurements of mass loss and size change were performed. The data have been presented in the form of standard drying kinetics. Additionally, the estimation of the diffusion coefficient according to the simplified graphical approach is made. Based on the best-fit approach the coefficients for typical semiempirical correlations for *MR* (moisture ratio) estimation have been calculated and presented.

Keywords: drying kinetics, diffusion coefficient, thin-layer, mathematical modelling, meat drying, shrinkage

Nomenclature

A	Area of samples (m^2)
D_{eff}	Effective moisture diffusivity (m^2/s)
M	Moisture content (g water/g dry solids)
MR	Moisture ratio (-)
N	Number of observations (-)
n	Number of parameters (-)
r	Cylinder radius (m)
R^2	Correlation coefficient (-)
$RMSE$	Root mean square error (-)
S	Shrinkage (-)
t	Time (s)
z	Cylinder height (m)
χ^2	Decreased chi-square (-)

Subscripts

e	Equilibrium content
exp	Experiment
i	Initial content
pre	Predicted
t	Specific time

INTRODUCTION

The nation's welfare is intrinsically tied to its food security as the availability of nourishing, high-quality food is essential for human survival. (FAO et al., 2021). In recent times, a multitude of significant factors has derailed global efforts to eradicate world hunger and malnutrition in all its manifestations by the year 2030. The obstacles have intensified due to the unprecedented spread of the COVID-19 pandemic and the subsequent implementation of relevant virus-related containment strategies. Thus, the sustainability and stability of agricultural production poses considerable challenges. Additional solutions are required for increasing the food output and availability to address population. Nevertheless, a significant portion of food products is often squandered through the production process (Osodo, 2018). An approximate 30% of nutrition worldwide goes to waste each year (EL-Mesery et al., 2022a). Alternative sustainable methods to minimize food wastage is being actively pursued worldwide, regardless of the country's economic status (Benhamza et al., 2021). Procedures in between gathering and consumption often include: sorting, cleaning, handling, packaging, storage, preservation, dehydration and shipping (Lockrey et al., 2019). Implementing a valuable post-harvest strategy ensures that the gathered nutrition not only

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meets buyers' expectations but also ensures customer satisfaction in terms of quality, availability, and safety (OECD, 2001).

Most agronomic goods typically retain a significant amount of moisture content upon harvest. Thus, these products are highly susceptible to decline in quality (X. Zhang et al., 2022). And if food products are not kept in thermally controlled storage facilities, rapid degradation of quality may end up spoiling them. Therefore, there are many advantages of food drying. The rottenness of agricultural products is a consequence of high moisture content that facilitates the growth of bacteria and fungi on these products. Drying is an essential method to decrease moisture content, effectively minimizing the spread of bacteria and fungi (Andlar et al., 2018; Mirza Alizadeh et al., 2021; Pham et al., 2022; Rajasekar et al., 2011; Sandikci Altunatmaz et al., 2012; Scherlach et al., 2013; Suvarnakuta et al., 2005). By diminishing the moisture content in agricultural products, the drying process plays a pivotal role in preserving food quality (EL-Mesery et al., 2022b). Consequently, it is widely recognized as the primary technique employed for conservation of edible goods (Castro et al., 2018; EL-Mesery et al., 2022b; Osodo, 2018). That is why drying processes are commonly used by food and agriculture industries to preserve a rising assortment of foods.

Investigating the drying behaviour of food is motivated by the rising concern about climate change and the necessity for the use of sustainable energy solutions in the food sectors. It is widely known that the moisture level of food items has a significant impact on the physicochemical and sensory changes that occur during drying. In this regard, a thorough comprehension and management of the drying process by precise moisture distribution prediction inside the product would lead to dried goods of higher quality. Additionally, by examining the impact of process factors, mathematical models may help forecast how food items will behave during drying. This can reduce the expense of the drying process and the degradation of the product's qualitative features.

The extensive research conducted to enhance our comprehension of moisture transfer in solids still is not sufficient. The main reason is due to the fact that, in practical applications, drying-rate curves rather have to be determined through experimentation than derived from underlaying theory (Erbay et al., 2010). Consequently, the significance of experimental studies in drying, particularly for food products, cannot be ignored. Several factors such as process conditions, the nature of the product, and the drying apparatus used are crucial variables in modelling thin-layer drying. Therefore, in literature, an ever-growing number of studies are conducted focused on mathematical modelling under the concept of the thin layer with simple empirical correlations (Ertekin et al., 2017). Variety of pre-treatments are carried out on raw food products to enhance drying and enhance product quality. These pre-treatments have a direct impact on the drying kinetics, and numerous researchers have utilized the thin layer concept to model the impact of different pre-treatments, particularly in the drying of fruits and vegetables.

A variety of dryers exist, catering to different raw materials and applications for the end product. The differences in the type of these dryers depend on the characteristics of the specific product being processed. Different types of dryers, such as tray dryers (Kiranoudis et al., 1997; Mugi et al., 2022; Raj et al., 2021; Saikia et al., 2022), spray dryers (Hernandez et al., 2021; Hernández et al., 2022; S. Zhang et al., 2021), freeze dryers (Barresi, Rasetto, et al., 2018; Barresi & Marchisio, 2018; Fissore et al., 2019; Marchisio et al., 2018; Scutellà et al., 2018), drum (Almena et al., 2019; Lee et al., 2022; Rodriguez et al., 1996a, 1996b) or roller dryers (Courtois, 2013), microwave dryers (Hazervazifeh et al., 2020; Kumar et al., 2022), etc., are widely used in the food industry. In-depth descriptions of these various dryer types, their benefits, and drawbacks, and how they apply to the appropriate food products are found in the literature (Anandharamakrishnan, 2017; M. Zhang et al., 2017). Additionally, there is a greater focus on drier structure and drying process optimisation. When it comes to food goods, two-criteria optimisation must be used to decrease energy consumption and achieve high-quality dry food items (Górnicki et al., 2007; Kaleta et al., 2002).

Convective drying involves the concurrent transfer of heat, mass, and momentum to eliminate moisture using hot air. A flow of air performs the task of heat transmission to the dried material. This energy is then passed onto the product's surface through convection and subsequently transferred within the product through either diffusion or convection, depending on material’s structural composition. As a consequence, the product's temperature rises, leading to the evaporation of water (Babu et al., 2018; Kahveci, 2017; Solomon et al., 2021; Vu et al., 2018; Whitaker, 1977). However, the process is energy-intensive and results in significant energy consumption. Therefore, the primary goal of food drying research is still to increase drying efficiency while retaining product quality (Khan et al., 2021).

The poor heat transfer coefficient of food and the protective layer present on agricultural goods make

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it difficult to remove moisture during hot air drying, which increases drying time and lowers overall product quality. As a result, methods for assisting hot air drying, such as hot water and steam blanching, hypertonic solution, and acid or alkali treatment, have been researched to address this deficiency (Du et al., 2022).

The drying rate and properties of the dried product are influenced by various external process conditions, including air temperature, humidity, velocity, and the direction of air flux. Furthermore, internal factors such as the geometry, thickness, shape, and structure of the product also affect the drying rate (Law et al., 2014; Mujumdar et al., 2000). The drying process of various food products poses a significant challenge due to factors such as the intricate structure and composition of the food, the presence of diverse transport phenomena, and the inherent biological variability. To effectively address these complexities, mathematical modelling, and simulation emerge as valuable tools (Chemkhi et al., 2005). By employing mathematical models and simulations, one can gain insights into the intricate nature of food product drying. These methods aid in understanding the complex interplay of variables and enable the identification of optimal operational conditions for the drying process. Through optimization, suitable parameters can be determined, enhancing the overall efficiency and effectiveness of the drying process.

Water distribution and status during drying have an impact on a material's physical and chemical qualities. Internal moisture diffusion in solids can be affected by various factors.

Zhu et al. (Zhu et al., 2021) studied the drying process for scallop adductors with pretreatment of the scallops with ultrasound. With an increase in ultrasound strength, the impact on the drying behavior of scallop adductors becomes greater. In this study 180 W ultrasound pretreatment was recommended for scallop drying, resulting in improved quality characteristics and a higher drying efficiency.

Many studies have been carried out dealing with the rehydration of food products namely such as apples and watermelon (Lingayat et al., 2020), green chili and okra (Goud et al., 2019), carrots (Mahapatra et al., 2018), zucchini, eggplant (Kılıç et al., 2019), sultana grapefruits (Karaaslan et al., 2017), mango (Mugodo et al., 2021), pumpkin (Benseddik et al., 2018), mushrooms (García-Pascual et al., 2005), pasta (Cunningham et al., 2007), chicken, (Schmidt et al., 2009) and pork meat (Muñoz et al., 2012; Uengkimbuan et al., 2006). The product types that have received the most extensive research are fruits and vegetables; however, the intriguing aspect lies in the notable potential of medical and aromatic plants for thin-layer drying. On the other hand, there are the fewest studies in the literature on the process of thin-layer drying of meat.

It is important to note that in a comprehensive review by Erbay and Icier (Erbay et al., 2010), authors indicate that fruits herbs, and vegetables constitute 92% of the total research. Therefore, modelling of meat products is considerably less developed and analyzed. These results prompted the author to investigate the drying process of popular sausage with a standard convective drying approach and visual observations of shrinkage. Therefore, the goal of this paper is to add an experimental data set for drying a meat product and provide a comparison with well-established thin-layer drying models.

MATERIALS AND METHODS

Drying procedure

Polish sausages from the local market have been selected and cut into samples of approximately 2 cm in diameter and 3 – 8 mm in thickness. The sausages were left in the convective food dryer. The inlet average temperature has been constant during the experiment, and the experiment has been conducted at a temperature of 40^{o}C. Periodically samples have been removed from the dehydrator, to measure their weight and average water content. Additionally, samples have been placed under a camera tripod to acquire images allowing for further analysis of dimensions' change.

Drying kinetics empirical models

Thin-layer drying models serve as potent instruments in the mathematical modelling of the dehydration process. These models depict the behaviour of food products during dehydration in a simplistic manner, rendering them applicable to a wide range of process parameters. Thin layer drying means that drying is in one layer of the food sample (Kavak Akpinar et al., 2006). Due to the fact of thin structure of the layer, the temperature distribution can be assumed as uniform. Therefore, thin-layer drying requires semi-theoretical equations and works well with lumped parameter models. Those models can be derived from Fick's second law of diffusion and modifications of its simplified forms. Other semi-theoretical models can be derived from analogy with Newton's law of cooling. Generally, these models are simpler than the theoretical ones and require fewer presumptions because some

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experimental data were used. However, they are only applicable within the limits of the procedure parameters that have been set.

These kinds of models estimate that the drying curve responds to an equation of the moisture ratio as a function of drying time. Moisture ratio (*MR*) can be calculated based on external circumstances. When the relative humidity remains unchanged throughout the drying procedure, the moisture balance also remains stable. Thus, MR can be determined from the following equation:

$$MR = \frac{M_t - M_e}{M_i - M_e} \qquad (1)$$

where: M_t is the moisture content at a specific time, M_i and M_e are respectively the initial and equilibrium content.

That simple analysis allows for a direct comparison of experimental data for specific conditions. The selected semi-theoretical models for various food products with their classification according to derivations have been shown in Table 1. In addition, the numerical modelling of food product dehydration necessitates the utilization of statistical methods for correlation analysis. Data regression id used in order to analyse relationships among different process variables. Diverse statistical techniques, including the correlation coefficient, can be employed to validate the accuracy of mathematical models (R^2), decreased chi-square (χ^2), and root mean square error (*RMSE*). These values are described by the equations 2, 3 and 4.

Estimation of the diffusion coefficient

Assuming that the samples may be roughly compared to cylinders, Fick's second law for non-steady-state diffusion states that the diffusion is represented by Eq. 5 (Yang et al., 2001). The analytical solution of Eq. (5) is provided by: assuming a uniform initial moisture content and a constant effective diffusivity throughout the sample (Eq. 6). The solution to Fick's equation is as follows when the first term of the series expansion in Eq. (6) is only taken into account Eq. 7. Eq. (4) can be rearranged, to the form (Eq. 8) proposed by (Mota et al., 2010).

Table 1. Representative empirical models under the concept of the thin-layer

Name	Mathematical equations
Page model (Page, 1949)	$MR = \exp(-kt^n)$
Modified Page model (G. M. White et al., 1980)	$MR = \exp[-(kt)]^n$
Logarithmic model (Chandra et al., 1995; Yagcioglu et al., 1999) (asymptotic)	$MR = a \exp(-kt) + c$
Midilli model (Midilli et al., 2002)	$MR = a \exp(-kt^n) + b^*t$
Modified two-term exponential model (Verma et al., 1985) (Verma model)	$MR = a \exp(-kt) + (1-a) \exp(-gt)$
Wang and Singh model (Wang et al., 1978)	$MR = 1 + b^*t + a^*t^2$

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sqrt{\left[\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right] \cdot \left[\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]}} \qquad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \qquad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - n} \qquad (4)$$

$$\frac{\partial M}{\partial t} = \frac{1}{r}\left\{\frac{\partial}{\partial r}\left(D_{eff} \cdot r \cdot \frac{\partial M}{\partial r}\right) + \frac{\partial}{\partial z}\left(D_{eff} \cdot r \cdot \frac{\partial M}{\partial z}\right)\right\} \qquad (5)$$

$$\frac{M_t - M_e}{M_i - M_e} = \sum_{n=1}^{\infty} \frac{4}{b_n^2} \exp\left[-D_{eff} \cdot \frac{b_n^2 \cdot t}{r^2}\right] \qquad (6)$$

$$MR = \frac{4}{b_1^2} \exp\left[-D_{eff} \cdot t\left(\frac{b_1^2}{r^2}\right)\right] \qquad (7)$$

$$\ln(MR) = \ln\left(\frac{4}{b_1^2}\right) + \left[-D_{eff}\left(\frac{b_1^2}{r^2}\right)\right] \cdot t \qquad (8)$$

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RESULTS AND DISCUSSION

The prepared samples have been arranged on the tray and placed in the dehydrator, to decrease the measurement error sixteen slices of the same thickness have been measured. The mass transfer rate was calculated as a mass loss per time between the measurements. Calculated values of the transferred mass during the experiment time data have been presented in Figure . As can be seen, the larger the thickness of the samples higher the amount of liquid evaporated in the process. This is a direct result of a higher mass of the samples and thus a larger amount of moisture present in specific samples. Additionally, all samples show a similar trend in moisture release.

In a different form of comparison, the same results have been referred to as the final mass of the sample (see Figure 2). This comparison shows a higher initial change in the rate of mass transfer and a steady value after the initial drying time. Initially the thinnest sample yields the highest moisture transfer rate due to the highest area-to-mass ratio. This trend changes after circa 5 hours of drying. Additionally, it can be seen that the difference between the thickest samples is diminishing.

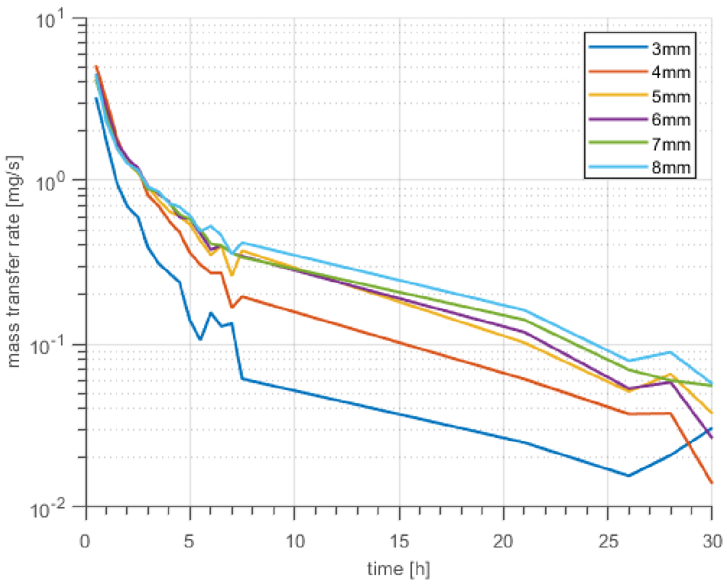

Figure 1. Drying rate over time for different slice thicknesses for the whole measured tray

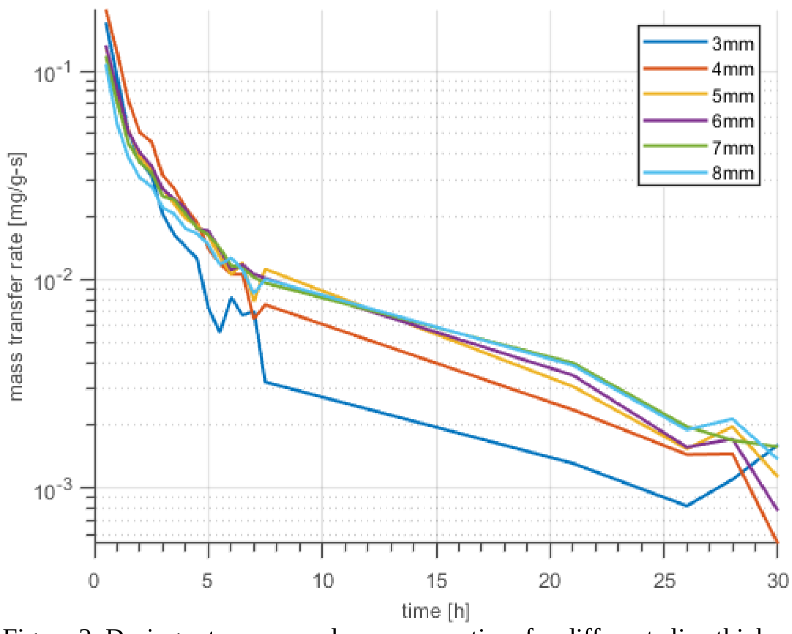

Figure 2. Drying rate per sample mass over time for different slice thicknesses

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Plotting of the experimental data for various slice thicknesses at the temperature under investigation (40 °C) has also been done using the dimensionless variable moisture ratio (*MR*), using Eq. (1), versus time (expressed in hours) and presented in Figure 3; the trends between *MR* and mass transfer rates are similar. The data series for the thickness of 6 and 5 mm stand out as nearly identical. The difference between series is more pronounced for decreasing the thickness of the samples.

Estimation of diffusion coefficients

As described in *Estimation of the diffusion coefficient* subsection, the analytical solution of the drying in a cylinder-shaped sample can be evaluated mathematically assuming a constant diffusion coefficient. The solution of the function based on the experimental values can be presented graphically. The logarithm of the moisture ratio (*MR*) has a linear form of experimental coefficients related to sample size and process parameters. Plotting values of *log(MR)* in the function of time allows for an estimate of the function slope and intercept values with the use of linear regression of the data. Figure 4 shows a set of experimental data along with a linear trend line.

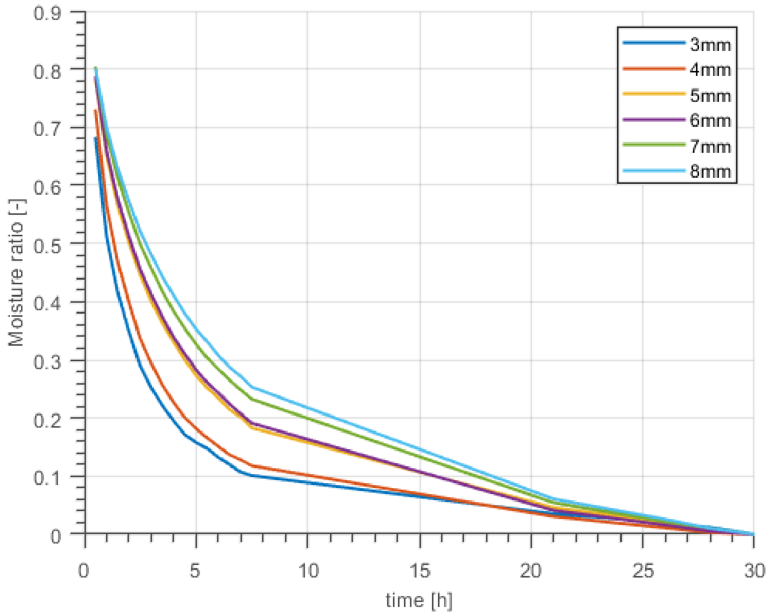

Figure 3. Calculated moisture rate for different slice thickness

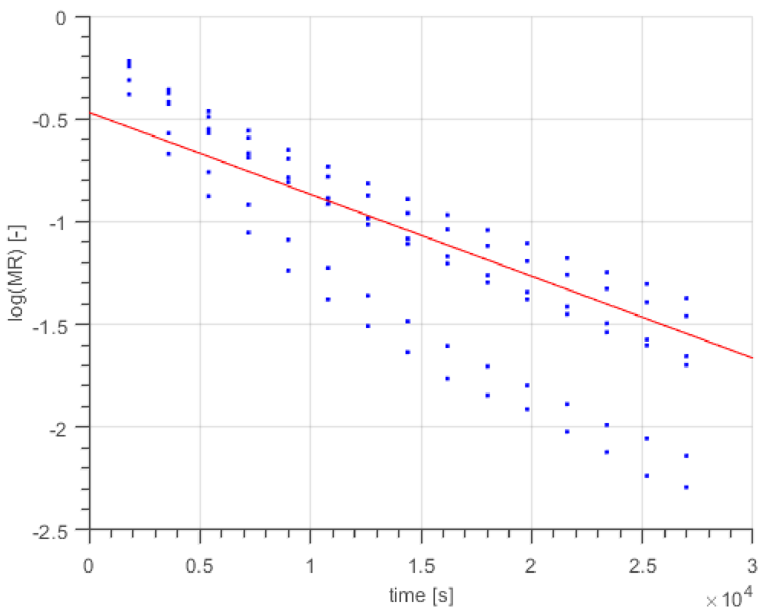

Figure 4. Graphical interpretation of diffusion coefficient D_{eff} calculation procedure

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As the experimentally obtained data for moisture ratio differ, regression of the data was made for all the data series. Obtained values are gathered in Table 2, overall, the D_{eff} values are similar for all the samples but with high differences in the case of the thinnest sample.

Table 2. Experimentally estimated values of diffusion coefficient D_{eff}

Sample thickness:	D_{eff} [m^2/s]
3mm	$3.081\ 10^{-4}$
4mm	$5.529\ 10^{-4}$
5mm	$6.232\ 10^{-4}$
6mm	$7.358\ 10^{-4}$
7mm	$6.874\ 10^{-4}$
8mm	$7.147\ 10^{-4}$

Statistical evaluation

Several semi-empirical models from the literature, were fitted to the experimental data sets of the moisture ratio change over time, i.e. Page (Page, 1949), logarithmic (Chandra et al., 1995; Yagcioglu et al., 1999), Midilli (Midilli et al., 2002), and Wang and Singh models (Wang et al., 1978). The correlation coefficient R^2 and root mean square error *RMSE* have also been determined statistically to assess the quality of each estimation. The models' statistical outcomes and the fitting results for the chosen models are displayed in Table 3. Obtained fit coefficients indicate that the best approximation has been obtained for logarithmic and Midili models. Other models were not shown due to fitting coefficients bringing functions to the same shape as the presented models.

Visual observations

The analysis of the shrinking process measurements using image data analysis has been carried out. In this analysis, the main focus has been placed on image fragmentation and shape recognition. The image processing has been done with the aid of the Image Processing Toolbox from the MATLAB application ("Matlab documentation," 2012). To measure the size changes of the analyzed sample during the drying process a segmentation mask to distinguish between the background and dried samples. During this process, the background has been cut out and indicated as black. Finally, the mask is taken from the analyzed image and the sum of pixels representing the samples was calculated. Figure 5 shows the basic process steps during a single image analysis.

Table 3. The fitting models and statistical results of the models

The thin-layer drying model	Model constant and coefficient of determination
Page model (Page, 1949)	$k = 2.02\ 10^{-3}; n = 0.6626;$ $R^2 = 0.8473; RMSE = 0.0719$
Logarithmic model (Chandra et al., 1995; Yagcioglu et al., 1999) (asymptotic)	$k = 6.61\ 10^{-5};\ a = 0.7894; c = 0;$ $R^2 = 0.8304; RMSE = 0.07578;$
Midilli model (Midilli et al., 2002)	$k = 7.824;\ a = 0.6587; n = -4.495;$ $b = -2.035\ 10^{-5};\ R^2 = 0.7561; RMSE = 0.0919$
Wang and Singh model (Wang et al., 1978)	$a = 1.817\ 10^{-9};\ b = -7.667\ 10^{-5};$ $R^2 = 0.7352;\ RMSE = 0.0947$

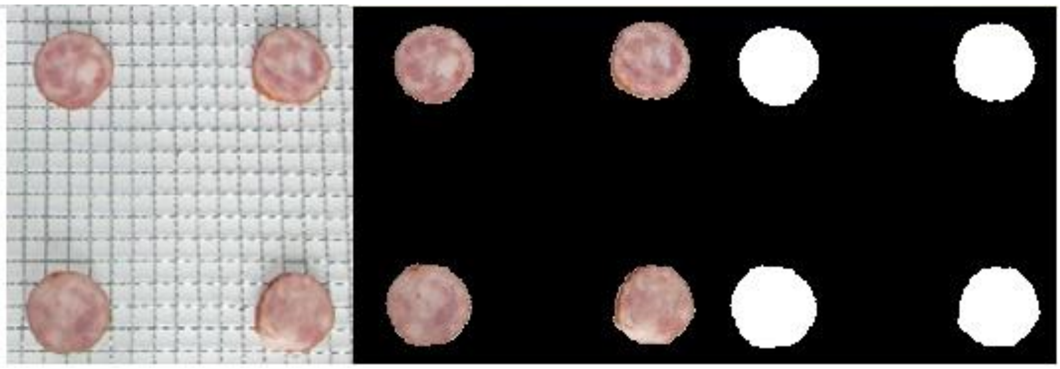

Figure 5. The sample of the mask generation process for sausage images

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The images have been taken directly during the weight between measurements. Finally, all processed images have been analyzed by in-house MATLAB code to evaluate the size change of the samples during the drying process. From the analyzed tray sample object areas have been calculated as active pixel sum, also main dimensions are estimated with a bounding box. An example of the procedure can be seen in Figure . A comparison of all the drying times and different samples with the processed binary mask can be seen in Figure .

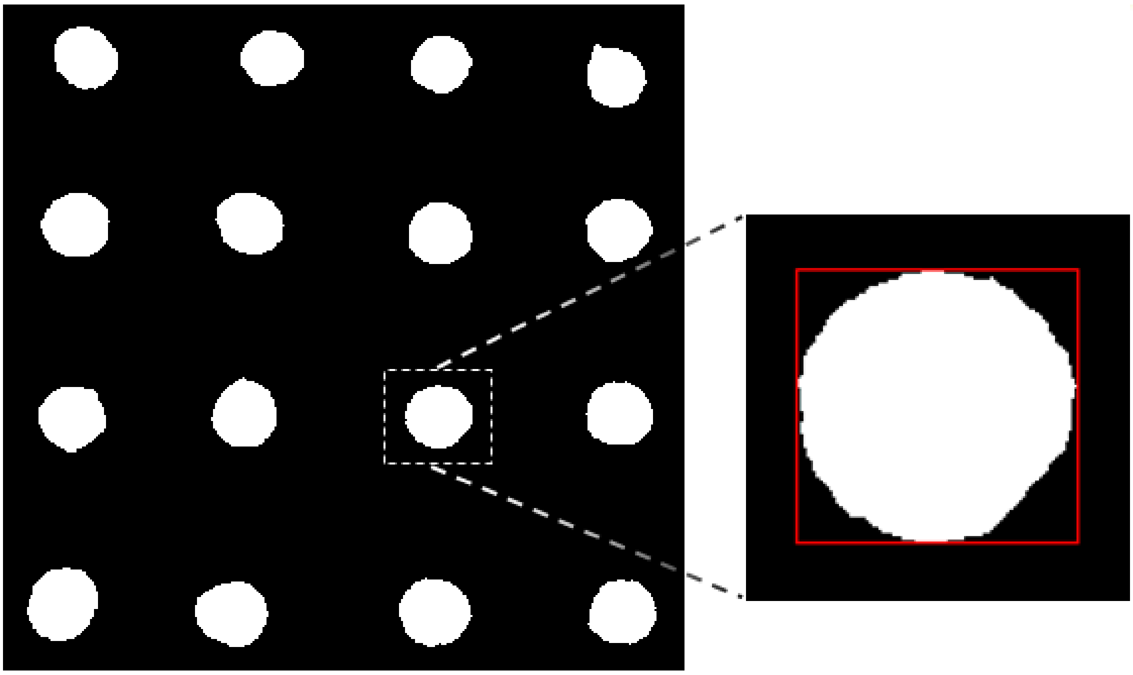

Figure 6. Calculation of dried samples area and main dimensions in terms of region properties

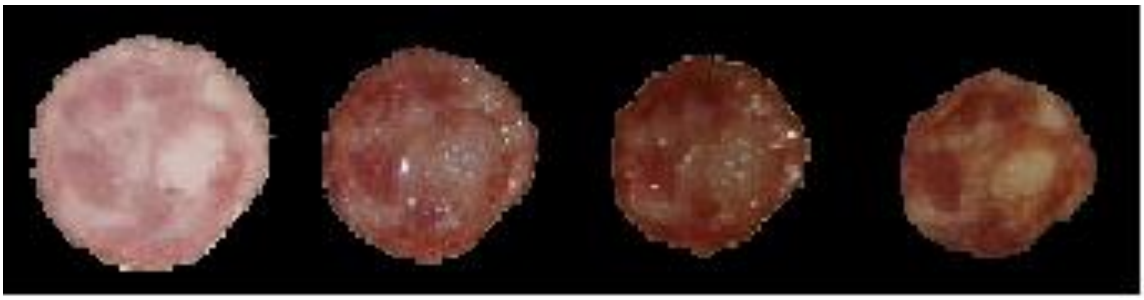

Figure 7. The original photos of sausage during drying stages with a binarized mask overlay

The number of pixels per sample directly corresponds to the area of the samples. Knowing the initial conditions and location of the samples they can be easily compared with the nondimensional shrinkage factor as presented in the following equation:

$$S = \frac{A_i - A_t}{A_i} \tag{9}$$

As can be easily seen from Figure 8 the biggest shrinkage has been observed in the case of the 3mm thick samples which corresponds to the highest amount of liquid evaporated per weight of the sample (as compared to Figure 2). A clear distinction can be seen between samples with lower thicknesses. The thicker sample analysis does not provide such a clear distinction. Overall, the shrinkage amount per sample corresponds with the amount of the transferred liquid. Also, according to literature studies (Yang et al., 2001). The shrinkage is mostly observed on the radius of the sample but shrinkage in the axis can be wrongly measured due to the bending of the skin of the sample. Thus, the thicker samples should be measured with additional means. Due to the limited time and procedure setup, individual thickness measurements were not performed in this study.

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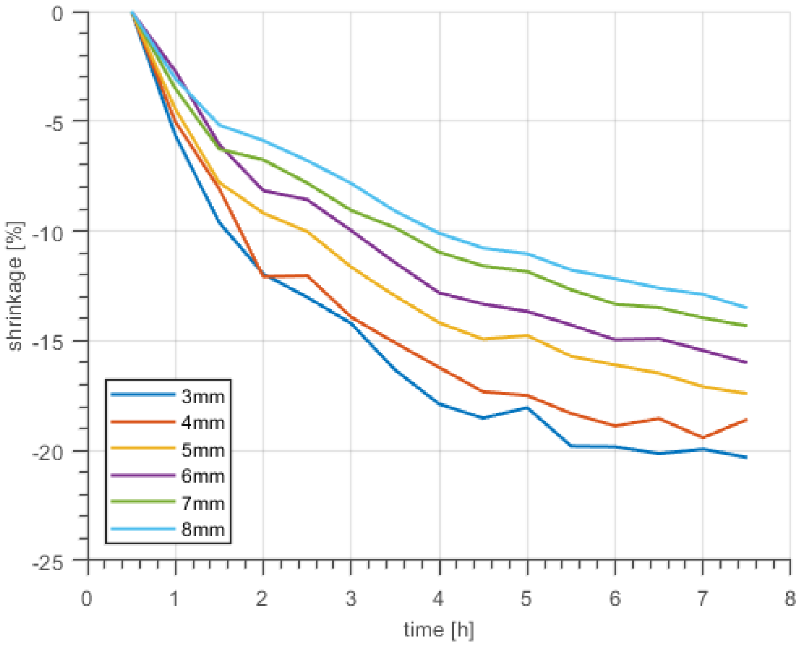

Figure 8. Calculation of dried samples area and main dimensions in terms of region properties

CONCLUSIONS

The goal of this paper has been to add an experimental data set for drying a meat product, which is of great importance in designing the drying process parameters. Thus it affects every aspect of food safety and developing of new dried meat products. Additionally, to provide a comparison with well-established thin-layer drying models. This article presented experimental investigations on the convective drying of Polish sausage slices. Slices have been prepared in a thickness of 3 to 8 mm.

The data have been presented in the form of standard drying kinetics. The experimental data points were best described with the Page model (Page, 1949). Based on the best-fit approach the coefficients for typical semiempirical correlations were calculated and presented. It has been observed that the thickness of the samples affected the rate of evaporated liquid according to expectations. Furthermore, the moisture transfer rate peer mass of the sample was highest in the initial part of the process for thinner samples, and it equalized for all the samples at the later stage of drying. In the drying time of 30 h, all the samples reached the equilibrium, and no additional mass transfer took place.

The estimation of the diffusion coefficient according to the graphical approach based on the theoretical diffusion model has been carried out. Due to the difference in the drying rate for varying slice thickness, the coefficients were calculated for every series individually. The obtained values of D_{eff}, for 4 to 8 mm slices are within 25 % from the highest calculated value. The difference is more pronounced in the thinnest samples of 3mm, in which the D_{eff} was two times lower.

The in-house MATLAB code was developed to automate the image processing and evaluate the size change of the samples. The results of the visual analysis indicate that the radial shrinkage of the material resembles the moisture ratio curve.

The shrinkage was observed to be related to the thickness of the sample. Where the thicker slices presented the lowest radial shrinkage. The difference in the shrinkage can be attributed to a dryer outer layers and more moisture in the core of the product.

In the future it is planned to expand experimental database and feed gathered data into the Machine Learning model in order to find dependencies between observed data.

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