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Foam-mat convective drying of kiwiberry (*Actinidia arguta*) pulp

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Abstract: The purpose of this work has been to determine the optimal conditions for the processing of kiwiberry fruit pulp based on the relevant thickness of the layer and air temperature, that will target the maximal reduction of drying time and minimal energy consumption. The research was designed to use the response surface methodology (RSM). The effects of independent variables (factors) such as the thickness of the layer (4, 8, and 12 mm) and the temperature of the drying air (50, 60, and 70°C) were studied by the means of the response variables. In this study, the drying kinetics was evaluated based on the drying time, drying rate, and effective water diffusion coefficient (D_{eff}). Based on the simplified Fick's second law of diffusion, D_{eff} was determined, while the relative water content [moisture ratio (MR)] was predicted using empirical models. It was found that as the temperature of the drying process increased, the process time was reduced, and the drying process intensified, which was manifested by the increment of the drying rate as well as the effective moisture diffusivity (varied from 5.58×10^{-10} m^2 s^{-1} to 27.2×10^{-10} m^2 s^{-1}). The mathematical model, developed using the RSM, showed a good fit for the data obtained in the study, which allowed to predict the response of the effective water D_{eff} of the foamed kiwiberry fruit pulp with $R^2 > 0.97$.

Keywords: mini kiwi; foam drying; drying kinetics; mathematical modelling; response surface methodology (RSM)

The foam is a specific material for drying and it is becoming increasingly used in the food industry. The drying allows to enhance the shelf life of plant materials with high water content (Wilson et al. 2012; Buljat et al. 2019). This technique allows to obtain a better quality of the product that has a higher porosity and may be easily reconstituted. Additionally, it allows to produce food in a powdered form that is convenient for further processing, transport, and storage and facilitates the removal of water from heat-sensitive food that is difficult to dry (Jakubczyk et al. 2010; Wilson et al. 2012; Sangamithra et al. 2015; Buljat et al. 2019). This is due to the open structure of the foam, which provides favourable conditions for the exchange of mass during the drying process. Moreover, the larger surface area exposed to the drying air and capillary diffusion also causes moisture removal to accelerate (Kandasamy et al. 2014, 2019; Sangamithra et al. 2015). The advantages of this method include a lower temperature of drying, shorter drying time, retention of nutritional quality, easy reconstitution, and the lower cost of powder output as compared to spray or freeze-drying (Hardy and Jideani 2015; Sangamithra et al. 2015; Ng and Sulaiman 2018).

The process of drying the foam-mat consists of the transformation from a liquid phase into a stable foam by applying foaming agents or stabilising agents. The next step is to spread the foam onto a thin sheet and then it is dried with air (Jakubczyk and Gondek 2009; Hardy and Jideani 2015; Sangamithra et al. 2015). The foamed material may be dried by means of various methods such as convective, microwave, microwave-convective, vacuum, infrared-convective drying, and sublimation (Jakubczyk et al. 2010; Azizpour et al. 2016).

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Foam drying requires optimisation of both the foaming process and the drying conditions. It should be considered that the foaming process is affected by many different factors, e.g. a chemical composition including sugar (saccharose, glucose, fructose) and organic acids (malic and citric acid), type and quantity of a foaming agent, and mixing time. On the other hand, the drying temperature, the airflow rate, and the thickness of the material layer have an impact upon the drying process (Sramek et al. 2015; Kandasamy et al. 2019). The foaming and stabilising substances (type and quantity) such as soy isolates, modified soy proteins, ovalbumin, methylcellulose, and maltodextrin have already been used for drying foamed materials. Exemplified use of this technique and those substances for the purpose of drying fruit or vegetable juice and fruit puree, jam, beverages, milk, and yoghurt can be found in the related literature. Jakubczyk et al. (2010) used the freeze-drying method for the foamed apple juice and concentrate with the addition of 2% albumin and maltodextrin, ranging from 0% to 40%. The maltodextrin addition enlarged from 10% to 40% resulted in the decreased hygroscopicity, bulk and tap density, while the flowability of the apple juice powder and wettability, as well as solubility of the apple concentrate powder, improved. Moreover, Ng and Sulaiman (2018) studied the possibility of the beetroot pulp foaming by means of egg albumin and fish gelatin and used foam-mat drying. They noted that the beetroot powder could be produced through that method and the beetroot pulp with fish gelatine showed better foam expansion and foam density, and after drying it was characterised by better hygroscopicity, water activity and more red colour powder as compared to the sample with egg albumin. Furthermore, the foam-mat drying method might be also used for drying yoghurt (Krasaekoopt and Bhatia 2012). Studies showed that a good quality yoghurt powder might be obtained when foaming agents, such as 3% egg albumin, were used and the material was dried at 60 °C for 3 h. In turn, Febrianto et al. (2012) dried the foamed fresh milk with the addition of varying amounts of Arabic gum and maltodextrin by means of the foam-mat drying technique, and the best results were obtained with the 15% addition of maltodextrin.

Recognition of the best parameters of drying processes is very important and sometimes difficult. Generally, drying processes are energy- and time-consuming, therefore it is worthwhile to use techniques such as the response surface methodology (RSM) to the extent of the selection of parameters for the optimisation purpose of the drying process. The RSM is one of the statistical tools that facilitate both the experiment design and related conclusions (Said and Amin 2015; Salehi et al. 2015; Shrimal et al. 2018). The RSM is a suitable group of mathematical and statistical techniques useful for fitting a quadratic surface. Moreover, it helps in the optimisation process with a minimum number of experiments (Behera et al. 2018). The RSM allows reducing the number of experiments compared to the number of experiments using a full factorial design. This method may be used not only to assess the influence of quantitative factors on the studied variables but also to determine the mutual relationships between those factors. The RSM also helps to determine the best experimental design and derive a model equation that may be later applied for the purpose of drawing conclusions, predicting response, and determining an adequate functional relationship between the parameters (Salehi et al. 2015; Behera et al. 2018). By applying this method, only a short period of time is required to test all variables, making the stage of the laboratory test more efficient, which then helps the scientist to focus on those particular variables that contribute to the product acceptance (Salehi et al. 2015). Thus, this work has aimed to analyse the impact of drying parameters at a varied thickness of the layer (4, 8, and 12 mm) and air temperature (50, 60, and 70 °C) to characterise the drying kinetics using a mathematical modelling approach.

MATERIAL AND METHODS

Experiment design. The experiment concerning the impact of drying parameters (layer thickness and air temperature) on the mathematical modelling of the convective dried kiwiberry fruit pulp was designed and analysed by means of Statistica 13 software (TIBCO Software, US). For this purpose, a two-level factorial design based on RSM and the face-centred central composite design (CCF) was used. Two factors were applied: A – layer thickness and B – air temperature. The experiment plan came forward with 11 experiments (Table 1) with a combination of each factor at each level with three repetitions at the 'central point' (8 mm, 60 °C, coded as 8_60 in Table 1) for each treatment.

Sample preparation. The experimental material contained the kiwiberry fruit (*Actinidia arguta* variety 'Bingo'). Plants grew on a commercial plantation under the supervision of scientists from the Department of Environmental Protection at Warsaw University of Life Sciences (WULS-SGGW), Poland. Fruits were collected at the eating maturity stage (soft) and were stored in darkness at a temperature of 4 °C

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in a cold store (KO-35; PPUCh Tarczyn, Poland). Before each experiment, fruits were withdrawn from the storage compartment, left to achieve room temperature (22 °C), washed with tap water, and shredded by hand with a metal strainer. The kiwiberry fruit pulp was foamed by means of a laboratory planetary robot (5KSM150; KitchenAid, Inc., US) with a 2% concentration of ovalbumin in fresh kiwiberry pulp. The obtained foam was spread onto aluminium trays of 300 × 150 × 20 mm in dimension and then dried. The thickness of the layer (D) of the drying material was 4, 8, and 12 mm. The initial weight of the spread samples ranged from 185.8 g to 273.5 g, and the weight of the tray was about 84.0 g. Drying was carried out until a constant mass was achieved.

Convective drying. The kiwiberry foamed pulp was dried in a laboratory prototype of convective dryer (Warsaw, Poland) at a temperature of 50, 60, and 70 °C with a parallel airflow at an air velocity of 2 m s^{-1}. The laboratory dryer drawing is presented in Figure 1. The initial moisture of the kiwiberry fruit pulp was measured using the vacuum drying Memmert VO400 (Germany) and proved the following parameters: 10 mPa, 70 °C, for 24 h (AOAC 2002), including the water content at 82 ± 2%. The dryer was coupled to an electronic balance (AG 4000; AXIS, Poland) with an accuracy of ±0.1 g and a measuring range from 1 g to 4 000 g. The airflow velocity was measured using Testo 440 thermo-anemometer (Testo SE & Co., Germany). The product was dried in the hot air flow that had been heated by the heater system placed on the air inlet. The temperature of the airflow was measured by the thermocouples. The thermal sensors and the balance were connected to the computer that recorded the data during the drying process by means POMIAR software (DOSBox v0.74; Radwag, Poland) in the DOS system, that actually allowed for recording the mass continuously (every 1 min) during the drying process. Drying was carried out until a constant weight was achieved.

Table 1. The scheme of two-factorial design – actual and coded factors' values

Runs	Factor A		Factor B		Sample code
	D (mm)	coded value	T (°C)	coded value	
1	4	–1	50	–1	4_50
2	4	–1	70	1	4_70
3	4	–1	60	0	4_60
4	8	0	50	–1	8_50
5	8	0	70	1	8_70
6	8	0	60	0	8_60
7	8	0	60	0	8_60
8	8	0	60	0	8_60
9	12	1	50	–1	12_50
10	12	1	70	1	12_70
11	12	1	60	0	12_60

D – layer thickness; T – air temperature

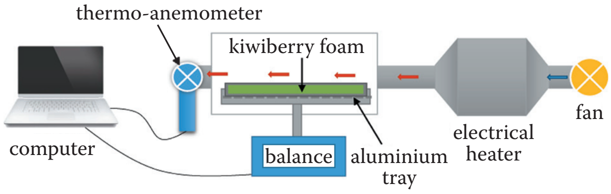

Figure 1. Scheme of the laboratory convective dryer

Mathematical modelling. The relative moisture ratio (MR) was calculated using Equation 1 (Wiktor et al. 2016):

$$MR = \frac{u_\tau}{u_0} \tag{1}$$

where: u_τ – moisture content at each moment of the process (kg kg^{-1}); u_0 – initial moisture content (kg kg^{-1}).

The effective water diffusion coefficient (D_{eff}) was computed according to simplified Fick's 2nd law of diffusion using Equation 2 for infinite slab (Salahi et al. 2015; Dehghannya et al. 2019). It assumes that D_{eff} remains constant throughout the process with no shrinkage of the material:

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}\tau}{4\left(\frac{D}{2}\right)^2}\right) \tag{2}$$

where: D_{eff} – diffusion coefficient (m^2 s^{-1}); τ – drying time (s), D – layer thickness (m).

The simplified Fick's 2nd law of diffusion was also used in order to determine the drying rate, which was calculated as the first derivative of the Equation 2 (Lammerskitten et al. 2019). Drying time was determined on the basis of drying curves [relationship between MR and drying time: $MR = f$(time)] as a time necessary to obtain by the samples MR = 0.15.

Statistical analysis. Regression analysis was performed using Table Curve 2D v5.01 software (SYSTAT Software, Inc., US). To evaluate model fit, coefficient of determination (R^2), reduced chi-square statistic (χ^2),

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root mean square error (*RMSE*), and coefficient of residual variation (*CRV*) (Wiktor et al. 2016) according to Equations 3–6.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{i,p} - MR_{i,e}\right)^2}{\sum_{i=1}^{N}\left(MR_{i,e} - MR_{p}\right)^2} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{i,p} - MR_{i,e}\right)^2}{N}} \quad (4)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{i,p} - MR_{i,e}\right)^2}{N - n} \quad (5)$$

$$CRV = \frac{\sqrt{\chi^2}}{Y} \times 100\% \quad (6)$$

where: $MR_{i,p}$ – predicted dimensionless moisture ratio; $MR_{i,e}$ – experimental dimensionless moisture ratio; MR_p – mean experimental moisture ratio; N – number of observations; n – number of constants in the model equation; χ^2 – reduced chi-square statistic; Y – average value of predicted moisture ratio.

RESULTS AND DISCUSSION

Drying characteristics. The kinetics curves of the kiwiberry fruit pulp drying process are presented in Figure 2. The kinetics depends on the air temperature and the thickness of the foam layer. It can be observed that the use of both the thickness of the foamed material layer and the drying air temperature, given their diverse combinations, had an impact on the process. The drying time to achieve MR = 0.15 for the thickest layer (12 mm) of the foamed kiwiberry fruit pulp at a low air temperature was the longest and the time of drying equalled 226 min (Table 2). As expected, the shortest drying time was obtained by a sample dried with the thinnest layer at the highest temperature (70 °C). Thus, it can be observed that with the increase in temperature, given the same thickness of the layer,

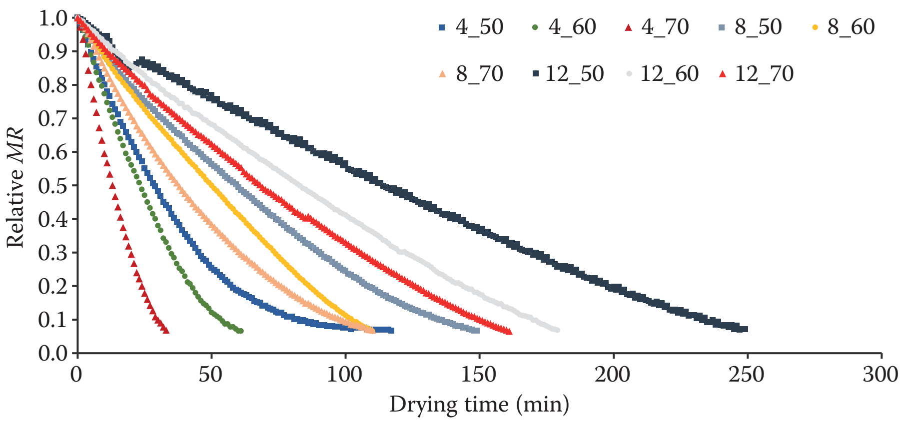

Figure 2. Drying kinetics of the foamed kiwiberry fruit pulp

MR – moisture ratio; for sample codes explanation, see Table 1

Table 2. Drying time (till MR = 0.15) and the results of statistical analysis of mathematical modelling of the foamed kiwiberry fruit pulp

Sample code	Drying time (min)	R^2	*RMSE*	χ^2	*CRV* (%)
4_50	117	0.989	0.0260	0.00069	6.9
4_60	53	0.989	0.0265	0.00076	5.4
4_70	28	0.989	0.0263	0.00080	5.4
8_50	125	0.988	0.0268	0.00074	5.3
8_60	96	0.980	0.0344	0.00123	6.5
8_70	90	0.997	0.0137	0.00019	2.9
12_50	226	0.976	0.0332	0.00073	5.0
12_60	162	0.981	0.0291	0.00079	5.2
12_70	141	0.987	0.0278	0.00079	5.4

MR – moisture ratio; *RMSE* – reduced chi-square statistic; χ^2 – root mean square error; *CRV* – coefficient of residual variation

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the drying time is reduced. Sramek et al. (2015) in their study found that the drying time of the foamed tomato pulp, using vacuum-drying, was comparable to the time of the convective drying. Other researchers noted that 10 °C increase in temperature reduced the drying time of the papaya pulp by half when the smallest layer (2 mm) was used (Kandasamy et al. 2019).

Mathematical modelling. The results of the regression analysis carried out for each combination of convection drying parameters tested for the foamed kiwiberry fruit pulp are shown in Table 2. Based on the analysis of the R^2 determination factors, it is plausible to state that the model showed a good fit for the experimental data, as demonstrated by the high values of statistical parameters. R^2 was between 0.976 and 0.997 and the lowest value was recorded for 12 mm and 50 °C drying. Moreover, low *RMSE* and χ^2 values, ranging from 0.0137 to 0.0344 and from 0.00019 to 0.00123, respectively, indicate a good fit of the selected mathematical model. The values of *CRV* up to 20% indicate the

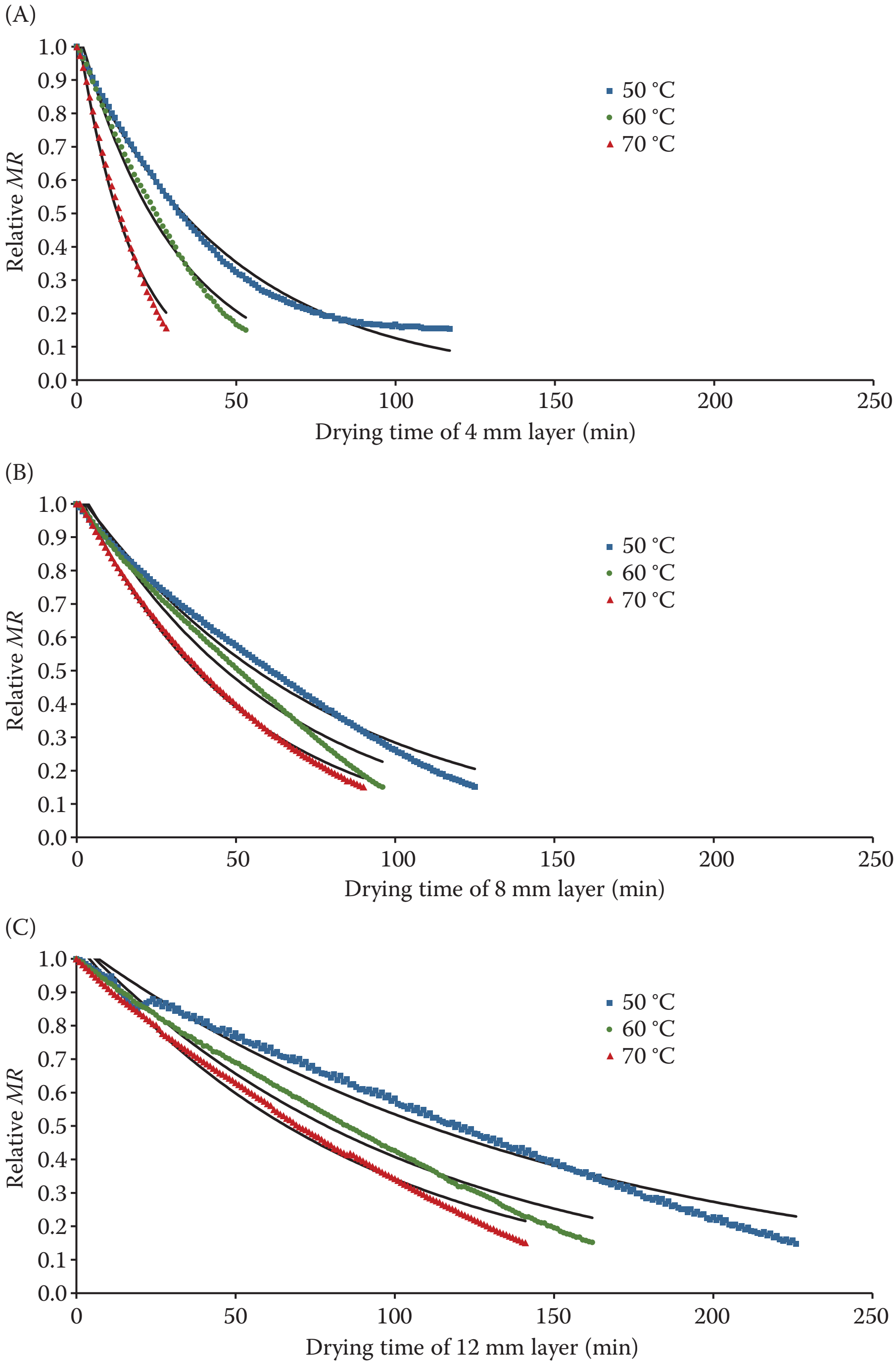

Figure 3. Drying curves of the foamed kiwiberry fruit pulp depending on the thickness of layer: (A) 4 mm, (B) 8 mm, and (C) 12 mm

MR – moisture ratio; black lines represent values obtained from the mathematical modelling

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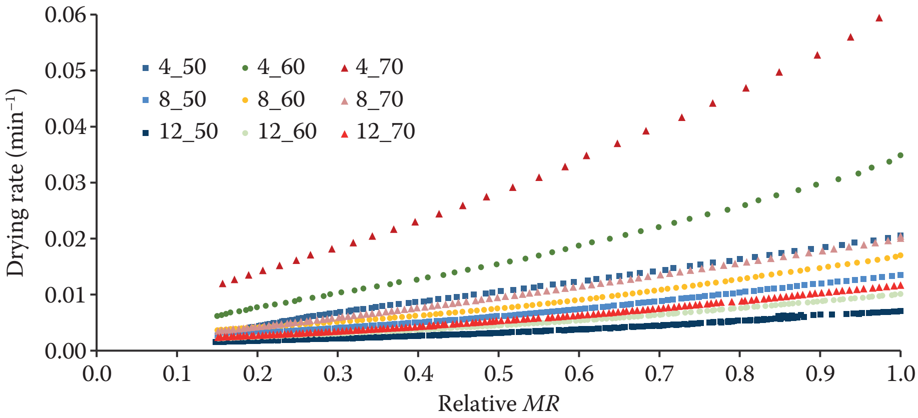


Figure 4. Drying rate of the foamed kiwiberry fruit pulp

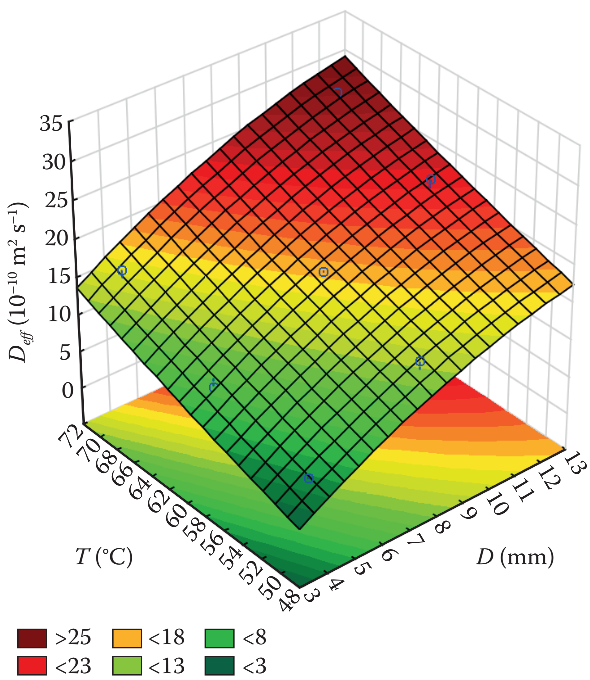
MR – moisture ratio; for sample codes explanation, see Table 1

practicability of the model. In this experiment, those values ranged from 2.9% to 6.5%, with the value being close to 5.0% for most of the tested samples.

The comparison of the experimental drying curves and the values predicted by simplified Fick's 2nd law of diffusion model according to Equation 2 (Salahi et al. 2015; Dehghannya et al. 2019) is presented in Figure 3. The results show that the drying curves depend on the process parameters that have been applied. Accordingly, it is plausible to state that both the increase in the layer thickness and the decrease in the drying air temperature affect the kinetics of the drying process of the plant material, extending the drying process. The layer of 12 mm in thickness and drying at 50 °C (sample code: 12_50) to obtain *MR* = 0.15 lasted 226 min, while a threefold reduction in the layer thickness at the same process temperature reduced the drying time to 117 min. Moreover, the increase in the drying temperature, given the same layer thickness, resulted in the acceleration of the drying process. It can therefore be concluded that the increase in the air temperature affects the intensification of the drying process, which was found in the drying of the foamy apple puree (Jakubczyk and Gondek 2009), concentrated tomato paste (Sramek et al. 2015) or papaya pulp (Kandasamy et al. 2014, 2019).

The drying rate of the samples of the kiwiberry fruit pulp, calculated in terms of the first derivative of *MR* = *f*(time) (Çakmak and Yıldız 2011; Wiktor et al. 2013), is presented in Figure 4. The highest initial drying rate (0.0631 min^{-1}) was obtained for the sample showing the layer of 4 mm in thickness, that was dried at a temperature of 70 °C, while the lowest drying rate (0.0070 min^{-1}) was reported for the pulp showing the highest thickness of the layer, that was dried at a temperature of 50 °C. Thus, a threefold increase in the layer thickness and the reduction of the drying temperature by 20 °C resulted in a 9-fold reduction in the initial drying rate. Similar results were achieved by Buljat et al. (2019) while they used a foam mat drying process for the production of the instant cocoa powder and the results confirmed that the temperature increase caused the drying rate to rise.

The relationship between the air temperature, layer thickness and the effective water D_{eff} is shown in Figure 5



$$D_{eff} = -17.032456140351 + 2.561951754386D - 0.08264802631579D^2 + 0.13350877192982T + 0.00252631578947737T^2 + 0.0043749999999999DT$$

Figure 5. Response surface of the effective water diffusion coefficient (D_{eff}) of the foamed kiwiberry fruit pulp

D – layer thickness (factor A); *T* – air temperature (factor B)

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in the form of the response surface chart. The model that has been developed can be written as follows:

$$D_{eff} = -17.033 + 2.562D - 0.083D^2 + \\ + 0.133T + 0.002T^2 + 0.0044DT \quad (7)$$

where: T – air temperature.

D_{eff} values ranged from 5.58×10^{-10} m^2 s^{-1} to $27.2 \times \times 10^{-10}$ m^2 s^{-1}. For food products, this coefficient takes the values from 10^{-11} m^2 s^{-1} to 10^{-9} m^2 s^{-1} (Bialik et al. 2017). The statistical analysis of the determined response surface model has proven that thickness and the air temperature alike play a significant role and linearly shape the value of the effective water D_{eff} (Figure 6). However, it is worth emphasising that thickness is characterised by a bigger effect when compared to air temperature. Such results are related to the fact that thickness plays a very important role in shaping the heat and mass transfer resistance. The proposed model has also exhibited a very good fit for the experimental data with $R^2 = 0.978$, which is also presented in Figure 7. The highest values of D_{eff} were noted for the samples with the highest layer thickness, that were dried at the highest temperature. The related literature contains the information that confirms that with the increase in the drying temperature, the D_{eff} value increases. For instance, Wilson et al. (2012), who dried the foamy mango pulp, observed that the D_{eff} value increased from

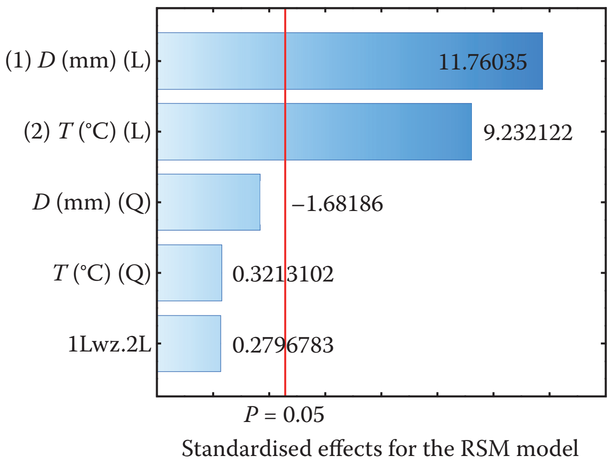

Figure 6. Pareto chart of standardised effects for the RSM model of the effective water diffusion coefficient (D_{eff}) of the foamed kiwiberry fruit pulp

RSM – response surface methodology; D – layer thickness (factor A); T – air temperature (factor B); 1Lwz.2L – linear interaction between T and D; L – linear effect; Q – quadratic effect

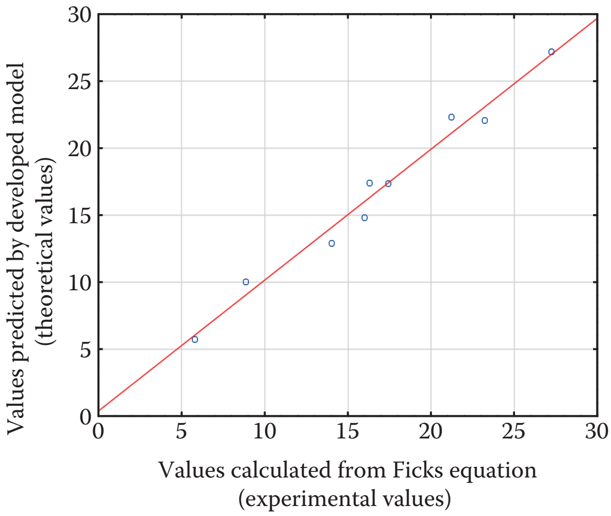

Figure 7. Schematic representation between values of the effective water diffusion coefficient (D_{eff}) 10^{-10} m^2 s^{-1} calculated from Fick's equation (experimental values) and values predicted by developed model (theoretical values)

1.5×10^{-8} m^2 s^{-1} to 2.6×10^{-8} m^2 s^{-1} with the temperature increasing from 65 °C to 85 °C. According to the literature-based data, temperature plays a major role among factors that affect the D_{eff} values. This temperature dependence is usually described in terms of the Arrhenius equation (Azzollini et al. 2016).

CONCLUSION

The course of the convective drying process (air temperature 50, 60, 70°C, airflow speed 2 m s^{-1}, and layer thickness 4, 8, and 12 mm) of the foamed pulp derived from the kiwiberry fruit has been well described by Fick's model. The use of higher temperatures during drying, given varied thickness allows to reduce the time of drying and intensification of its course. In addition, the reduction of the layer thickness allows to reduce the duration of the process, with the values of the other parameter (air temperature) remaining unchanged. Moreover, the increase in the drying air temperature increases the value of the effective water diffusion coefficient (D_{eff}).

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