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Suitable model for thin-layer drying of root vegetables and onion

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A b s t r a c t. The drying behaviour of carrot, parsley, red beetroot and onion slices of 5 and 10 mm thickness was investigated in a convective dryer at a drying temperature of 50, 60 and 70°C under natural convection conditions. The experimental drying data of the vegetables slices obtained were fitted to five empirical thin-layer models: Lewis (Newton), Henderson and Pabis, Page, Modified Page, Wang and Singh. The effects of the vegetable species, air drying temperature, and slice thickness on the model parameters were determined. Four statistical tools, namely, the determination coefficient, root mean square error, reduced chi-square, and *t*-statistic method were applied to determine the fittings. The Page model with the model parameters determined by a summation equation, a square type dependence for the drying air temperature and a rational one for the slice thickness is recommended as the most suitable model (R^2 = 0.9699, *RMSE* = 0.0587, χ^2 = 0.0035, *t*-stat = 0.6739).

K e y w o r d s: root vegetables, onion, drying kinetics, modelling, drying models

INTRODUCTION

Drying is one of the oldest and most common operations in the food industry. Food products are usually dried to maintain food safety because the process reduces both enzymatic and microbial changes during the storage period and thereby improves the shelf life of the product (Younis *et al.*, 2018). Large quantities of fruits, vegetables and other plant tissues are also dried to reduce their weights and packaging costs, enhance appearance, and maintain flavour and nutritional values. Although the enhancement of product quality, economic considerations, and environmental concerns are the main aims of the drying process, the most important objective is preservation which depends on the drying mechanisms (Barba *et al.*, 2014).

The process of drying moist food involves a combination of heat and mass transfer. Therefore, the drying process could be described as moisture removal by means of simultaneous heat and mass transfer between the product and the surrounding air. The moisture is removed mainly by vaporization which occurs for the most part due to temperature and air convection forces (Avhad and Marchetti, 2016).

Studying the drying kinetics may be of particular relevance in choosing the optimal conditions for a satisfactory drying process (Opalić *et al.*, 2009). Full-scale experimentation with different bioproducts and system configurations is in the main costly and therefore impractical. Hence, the mathematical modelling of the drying processes and equipment is a very important issue for drying technology. The development of a mathematical model for the drying process allows for the selection of the most adequate operating conditions and hence the most appropriate size of the drying equipment which enables it to meet the desired operating parameters (Sacilik *et al.*, 2006).

Drying behaviour is described using the following categories of mathematical models: theoretical models, semi-theoretical models, and empirical models (Rodríguez *et al.*, 2014).

Theoretical models are based on the theory of mass and heat transfer laws. They respect the fundamentals of the drying process and their parameters have a physical meaning. Theoretical simulations may provide explanations for various phenomena, which occur during the drying process. However, the models discussed are time consuming because the diffusion equations governing the process are complicated (Kaleta and Górnicki, 2010b). Theoretical

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models have been applied to describe the drying kinetics of such biological materials as apples (Kowalski and Rybicki, 2017), carrots (Mahapatra and Tripathy, 2018; Sánchez-Sáenz *et al.*, 2015), cherry tomato (Bennamoun *et al.*, 2015), green bean (Doymaz *et al.*, 2015; Tekin *et al.*, 2017), hazelnut (Giraudo *et al.*, 2018), peach (Doymaz, 2014), pumpkin (Agrawal and Methekar, 2017; Junqueira *et al.*, 2017), peppermint leaves (Ashtiani *et al.*, 2017), poppy seeds (Stakić and Urošević, 2011), pre-gelatinized potato starch (Jiang *et al.*, 2017), red beets (Kaleta and Górnicki, 2010b), spinach leaves (Doymaz, 2009), and sunflower seeds (Darvishi *et al.*, 2013).

Recently, a research study has modelled drying kinetics using artificial neural networks (Omari *et al.*, 2018; Özdemir *et al.*, 2017; Rodríguez *et al.*, 2014).

The semi-theoretical models are generally deduced from simplified versions of Fick's second law of diffusion (Ashtiani *et al.*, 2017). The empirical models are mainly formulated from the direct relationship between the moisture content and drying time (Ertekin and Firat, 2017). Mathematical equations obtained in this way have parameters, which are fitted based on the experimental results. The mathematical form of empirical models does not require the consideration of the theory of drying, therefore their parameters are without physical meaning (Kaleta *et al.*, 2013). On account of their simplicity, the models discussed are applied to describe the drying characteristics of different products such as apples (Antal *et al.*, 2015; Atalay *et al.*, 2017), blueberries (Yu *et al.*, 2017), carrots (Aghbashlo *et al.*, 2011; Mahapatra and Tripathy, 2018), canola (Gazor and Mohsenimanesh, 2010), cashew (Dhanushkodi *et al.*, 2017), dill leaves (Motevali *et al.*, 2013), garlic (Younis *et al.*, 2018), green bean (Doymaz *et al.*, 2015; Tekin *et al.*, 2017), Hass avocado seeds (Avhad and Marchetti, 2016), kiwi fruit (Tian *et al.*, 2015), Moroccan rosemary leaves (Mghazli *et al.*, 2017), peach (Doymaz, 2014), pumpkin (Junqueira *et al.*, 2017), rice (Hacıhafızoğlu *et al.*, 2008), spinach leaves (Doymaz, 2009), sweet basil (Phoungchandang and Kongpim, 2012), tomato (Azeez *et al.*, 2017), *Vernonia amygdalina* leaves (Alara *et al.*, 2017). Some authors have described the effect of drying variables on the parameters of empirical models, in these cases such models may be considered to be more general. In the literature, the predicted parameter values were correlated as a function of drying air temperature (Alara *et al.*, 2017; Kaleta *et al.*, 2013; Mghazli *et al.*, 2017), drying air temperature and airflow velocity (Hosseinabadi *et al.*, 2012), characteristic particle dimension and initial material load (Kaleta *et al.*, 2013), airflow velocity, drying air temperature, characteristic particle dimension and the initial height of the layer (Kaleta and Górnicki, 2010a), wood species and drying air temperature (Górnicki *et al.,* 2017). No information was obtained concerning the examination of the effect of the vegetables species on the parameters of the drying models. Therefore, the objective of this paper was to investigate the effect of the vegetable species, drying air temperature and slice thickness on the parameters of the drying models.

As mentioned previously, some authors have described the effect of drying variables on the parameters of the empirical models in order to make these models more widely applicable. The effect of the type of the material being dried was only determined for wood (Górnicki *et al.,* 2017). Therefore, the authors investigated the effect of conditions of conducting drying process (air drying temperature, slice thickness) and also the effect of differences in the biological and mechanical structure of vegetables.

MATERIAL AND METHODS

Onions and roots of carrot, parsley, and red beet were obtained from a local market. The material was washed in water, hand peeled, and cut into slices (5 and 10 mm thickness) with a cutting machine, and then dried on the same day. The initial moisture content varied between 9.29 and 9.72 kg H_2O kg^{-1} d.m. for carrot, 4.77 and 5.24 kg H_2O kg^{-1} d.m. for parsley, 7.55 and 8.00 kg H_2O kg^{-1} d.m. for red beet, 7.10 and 8.80 kg H_2O kg^{-1} d.m. for onion. The product moisture content was determined according to the standard procedure (Horwitz, 2005).

The experiments were conducted in a laboratory dryer – Memmert UFP400 (MEMMERT GmbH+Co. KG, Schwabach, Germany) – under natural convection conditions. Three drying air temperatures namely, 50, 60, and 70°C were used in the experiments. The measurements were performed in the following manner. The sample was uniformly spread as a thin-layer on the tulle stretched on a metal frame (scale) and then hung up on the scales WPX 650 (RADWAG, Radom, Poland). The weighing accuracy was ±1 mg. Changes in the sample mass were recorded each 60 s using a computer connected to the scales. Drying was continued until there was no mass change. The experiments were performed in three repetitions.

The air temperature inside the dryer was measured using thermocouple TP-01b-W3 (CZAKI THERMO-PRODUCT, Raszyn, Poland). The thermocouple was placed at the centre of the drying chamber. The temperature was measured with ± 0.1°C accuracy.

Table 1 shows the empirical models applied to describe the drying characteristics of carrot, parsley, red beetroots and onions (*a*, *b*, *k*, and *n* are the model parameters). Simple models with only one or two parameters were chosen. These drying models are very often used, especially in practical drying.

The dimensionless moisture ratio *MR* is calculated using Eq. (1):

$$\mathrm{MR}=\frac{M_t\text{-}M_e}{M_0\text{-}M_e}\,, \qquad (1)$$

where: M_t is the moisture content at t (kg H_2O kg^{-1} d.m.), t is time (s), M_e is the equilibrium moisture content (kg H_2O kg^{-1} d.m.), and M_0 is the initial moisture content (kg H_2O kg^{-1} d.m.).

The initial and equilibrium moisture content of the samples were determined gravimetrically by drying in a laboratory oven at a temperature of 105°C and atmospheric pressure for a period of 24 h, until completely dry (Lutovska *et al.*, 2017).

The drying curves obtained from the experiments were fitted to the five tested models presented in Table 1. The data were analysed using the computer program Dell Statistica (ver. 13; Dell Inc., Tulsa, OK, USA). A non-linear regression analysis was carried out using the Lavenberg-Marquardt method and thus the model parameters were determined. When statistical analyses are carried out to identify the best fit, frequently used statistical criteria are the determination coefficient (R^2), reduced chi-square (χ^2), the root mean square error (*RMSE*), and the t-static method (*t*-stat) (Azeez *et al.*, 2017; Kaleta *et al.*, 2013). The criteria mentioned above may be calculated using Eqs (2)-(5):

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

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\text{pre},i}\text{-}MR_{\exp,i}\right)^2\right]^{1/2}, \tag{3}$$

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

$$t\text{-stat} = \left[\frac{(n\text{-}1)MBE^2}{RMSE^2\text{-}MBE^2}\right]^{1/2}, \tag{5}$$

where: MR_{exp} and MR_{pre} are dimensionless moisture ratios obtained from experimental results and modelling, respectively, N is the number of observations, n is the number of parameters in the drying model, i is the number of terms, and *MBE* (mean bias error) is calculated according to Eq. (6):

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{\text{pre},i}\text{-}MR_{\exp,i}\right), \tag{6}$$

where R^2 takes the values between 0 and 1. The closer it is to 1, the closer the relationship between the experimental and predicted values. The *RMSE* value is required to reach 0. Lower *RMSE* values indicate better fitness of the established model. The lower the values of χ^2 and *t*-stat, the better the goodness of the fit.

The effect of the vegetable species (VS), drying air temperature (T, °C), and slice thickness (L, mm) on the model parameters were investigated in the following manner. The parameters of the applied models 1-5 involving the considered variables were obtained by taking into account the following equations: summation: X=f(VS)+f(T)+f(L), subtraction X=f(VS)-f(T)-f(L), multiplication X=f(VS) f(T) f(L), division X=(f(VS)/f(T))/f(L), (X is the variable). The influence of T was described by applying several different equations, namely: linear f(T)=A+B T, logarithmic (common) f(T)=A+B log(T), rational f(T)=A+B T^{-1}, square f(T)=A+B T+C T^2. A, B, C are coefficients independent of the vegetable species and slice thickness. The influence of L was expressed by accepting the following type of dependencies: linear f(L)=D+E L, logarithmic (common) f(L)=D+E log(L), rational f(L)=D+E L^{-1}, and square f(L)=D+E L+$F$$L^2$. Coefficients D, E, F are independent of the vegetable species and drying air temperature. The influence of VS on the drying model parameters was determined using the A_v coefficient (f(VS) = A_v). A_v is the coefficient independent of T and L and its value depends only on the type of vegetable.

RESULTS AND DISCUSSION

The moisture ratio versus time diagram for the drying of the investigated vegetables is presented in Fig. 1. Each of the drying curves $MR(t)$ represents an empirical formula. The empirical formula approximates the results of three measurement repetitions of the moisture ratio changes over time. It may be assumed that the drying process of the slices of the considered vegetables was affected by the vegetable species. Figure 1 shows that the drying time for carrot and red beetroots and onions may be regarded as almost the same. It may be observed that the drying process of parsley root slices is slower than that of other vegetable species, however, the drying time may be considered to be the same. The same trends that were observed for drying at 70°C were obtained at 50 and 60°C, and for slices of 10 mm thickness.

There is no information in the literature concerning a comparison of the drying curves of carrots, parsley, red beets, and onions although the drying process of these vegetables were investigated (Górnicki and Kaleta, 2007; Planinić *et al.,* 2005; Shynkaryk *et al.,* 2008).

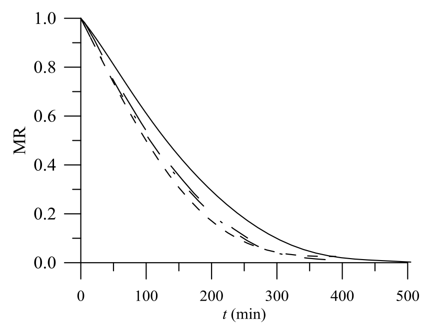

Fig. 1. Moisture ratio versus time for drying the investigated vegetable species slices of 5 mm thickness at 70°C air temperature: (—) parsley, (— —) onion, (— · —) carrot, (- - -) red beet.

Table 1. Considered thin-layer models

Model No.	Model equation	Model name	References
1	$MR(t) = \exp(-kt)$	Lewis (Newton)	(Lewis, 1921)
2	$MR(t) = a\exp(-kt)$	Henderson and Pabis	(Henderson and Pabis, 1961)
3	$MR(t) = \exp(-kt^n)$	Page	(Page, 1949)
4	$MR(t) = \exp[-(kt)^n]$	Modified Page	(Overhults *et al.*, 1973)
5	$MR(t) = 1 + at + bt^2$	Wang and Singh	(Wang and Singh, 1978)

Table 2. Results of statistical analyses in describing the drying model parameters using a summation and subtraction equation

Model No.	Parameter	R^2	*RMSE*	χ^2	*t*-stat
1	*k*	0.9682-0.9703	0.0003	0.0000	0.0010-0.0486
2	*k*	0.5073-0.6294	0.0012-0.0014	0.0000	0.0000-0.0114
	a	0.5117-0.6283	0.0158-0.0181	0.0003-0.0004	0.0000-0.0016
3	*k*	0.1999-0.4124	0.0004	0.0000	0.0000-0.0178
	n	0.6481-0.7342	0.0431-0.0500	0.0021-0.0028	0.0000-0.0012
4	*k*	0.9681-0.9752	0.0003	0.0000	0.0000-0.0127
	n	0.6419-0.7342	0.0431-0.0500	0.0021-0.0028	0.0000-0.0019
5	*a*	0.9404-0.9453	0.0003	0.0000	0.0002-0.0291
	b	0.8743-0.8771	0.0000	0.0000	0.0001-4.8603

Table 3. Results of statistical analyses concerning the modelling of the drying process of carrot, parsley, red beet and onions (the model parameters are described by summation, subtraction, multiplication and division equations)

Model No.	R^2	*RMSE*	χ^2	*t*-stat
1	0.9604-0.9620	0.0672-0.0682	0.0045-0.0047	1.0704-1.4191
2	0.9503-0.9570	0.0718-0.0768	0.0053-0.0060	4.0153-6.6940
3	0.9690-0.9699	0.0587-0.0600	0.0035-0.0037	0.6739-2.5203
4	0.9688-0.9701	0.0587-0.0600	0.0035-0.0037	2.0100-2.5548

An evaluation of the empirical models was applied to describe the drying characteristics of carrot, parsley, red beetroots and onions, it was carried out in the following manner. The moisture content data received from the experiments for different *T* and *L* values were changed to a dimensionless moisture ratio formula. The next step was the curve fitting computations with the drying time taking into account the models given in Table 1. Then the regressions were taken into account to explain the influence of the vegetable species, air temperature, and slice thickness on the parameters of the models under considerations. The effects of VS, *T*, and *L* on the model parameters were also included in the models. The following types of dependencies were examined: summation, subtraction, multiplication, and division. Linear, rational, logarithmic (common), and square types of equation were applied for the air drying temperature and slice thickness. The parametes combinations giving the highest values of R^2 were then considered in the final model. The dependencies obtained, along with the determined coefficients were then applied to calculate the moisture ratio of carrot, parsley, red beetroots and onions at any time during the drying process. The models developed were validated by comparing the measured and computed moisture ratios in any particular drying course.

Statistical analyses indicated that the parameters of the models determined by summation and subtraction equations (with the linear, logarithmic (common), rational, and square types of equation for the air drying temperature and slice thickness) may be assumed to be appropriate for the five drying models under consideration (Table 2). The *RMSE* values varied between 0.0000 and 0.0500, the χ^2 values ranged from 0.0000 to 0.0028, while the *t*-stat values ranged from 0.0000 to 0.0486 (for model 5 from 0.0001 to 4.8603). The values of the determination coefficient (R^2) are slightly less satisfactory and for models 1, 2, 4, and 5 they varied from between 0.5073 and 0.9752, however, for model 3, the R^2 values ranged from 0.1999 to 0.7342.

All of the parameter equations discussed above were then substituted into the tested models to predict the course of the drying curves for carrot, parsley, and red beetroos and onios slices of 5 and 10 mm thickness in the temperature range of 50-70°C. The results of the statistical analyses are presented in Table 3. The results for the Wang and Singh

Table 4. Coefficients of the chosen parameter equations for drying models and the results of statistical analyses concerning the modelling of the drying process of carrot, parsley, red beet and onions

Parameter equation	A_v				A	B	C	D	E	F	R^2	*RMSE*	χ^2	*t*-stat
	Carrot	Parsley	Red beet	Onion										
Model No.														
1														
$k=A_V+(A+BT)+(D+EL^{-1})$	0.00115	0.00038	0.00154	0.00077	0.00250	0.00013	-	-0.01001	0.02483	-	0.9620	0.0672	0.0045	1.3977
2														
$k=A_V-(A+BT)-(D+EL+FL^2)$	0.00443	0.00148	0.00590	0.00295	-0.01137	-0.00009	-	0.04549	-0.00941	0.00067	0.9503	0.0754	0.0058	4.0153
$a=A_V-(A+BT)-(D+EL+FL^2)$	0.06492	0.02164	0.08656	0.04328	0.19910	-0.00029	-	-0.79640	-0.11838	0.00843				
3														
$k=A_V+(A+BT+CT^2)+(D+EL^{-1})$	0.00020	0.00007	0.00027	0.00014	0.00557	0.00061	0.00000	-0.02228	-0.00317	-	0.9699	0.0587	0.0035	0.6739
$n=A_V+(A+BT+CT^2)+(D+EL^{-1})$	0.01774	0.00591	0.02365	0.01183	-0.82778	-0.05457	0.00048	3.31112	1.57325	-				
4														
$k=A_V-(A+BT)-(D+EL)$	0.04097	0.01366	0.05463	0.02732	0.00005	-0.00012	-	0.00003	0.00049	-	0.9695	0.0593	0.0036	2.0100
$n=A_V-(A+BT)-(D+EL)$	0.00121	0.00041	0.00162	0.00081	-0.82708	-0.00274	-	-0.41354	0.03078	-				

model (model 5) are not inserted into Table 3 because they turned out to be unacceptable. The other tested models, namely: Lewis (Newton) (model 1), Henderson and Pabis (model 2), Page (model 3), and Modified Page (model 4) fitted very well to the experimental data. The determination coefficient values are high enough (0.9503-0.9701), *RMSE* varied between 0.0587 and 0.0768, χ^2 ranged from 0.0035 to 0.0060, and the *t*-stat value varied from 0.6739 to 6.6940.

The effect of VS, *T*, and *L* on the model parameters may be taken into consideration on an individual basis (Table 4). The coefficients of the chosen parameter equations for carrot, parsley, red beetroos and onios drying models are shown in Table 4. The A_v parameter has different values for different vegetables, which indicates the effect of the type of vegetable (A_v depends on the vegetable species) on the kinetics of the drying process (Fig. 1). By substituting these coefficients into parameter equations and then considering the aforementioned formulas in the examined models, the course of the drying curve of the considered vegetables may be predicted. The parameter equations given in Table 4 are those, which were substituted into an adequate drying model to allow for the most precise description of the drying curves. The results of statistical analyses for the examined descriptions are presented in Table 4. It may be stated that the following models: Lewis (Newton) (model 1), Henderson and Pabis (model 2), Page (model 3), and Modified Page (model 4) with parameter equations adequate for each considered model given in Table 4 fitted very well to the experimental data. Figure 2 confirms the existence of an acceptable correlation between the experimental and predicted moisture ratios (for all considered vegetables) and shows that the considered models are appropriate for predicting the drying characteristics of carrot, parsley, red beetroots and onions.

To summarize, the drying models given in Table 4 may be used to describe the drying kinetics of carrot, parsley, red beetroos and onios slices of 5 and 10 mm thickness in the temperature range of 50-70°C. The Page model with parameters evaluated using a summation equation and square type dependence for drying air temperature and a rational one for slice thickness may be considered, however, as the most satisfactory model (R^2=0.9699, *RMSE*=0.0587, χ^2=0.0035, *t*-stat=0.6739). The statistical analyses results describing the Page model parameters using the dependencies mentioned above are the following: R^2=0.4017, *RMSE*=0.0004, χ^2=0.0000, *t*-stat=0.0126 for *k* and R^2= 0.7194, *RMSE*=0.0442, χ^2=0.0022, *t*-stat=0.0004 for *n*.

The investigations revealed that there is a possibility of generalizing the empirical models considered. The inclusion of the appropriate VS material coefficient into the parameters of these models gives the chance of predicting the drying process of various vegetables with a significantly high degree of accuracy.

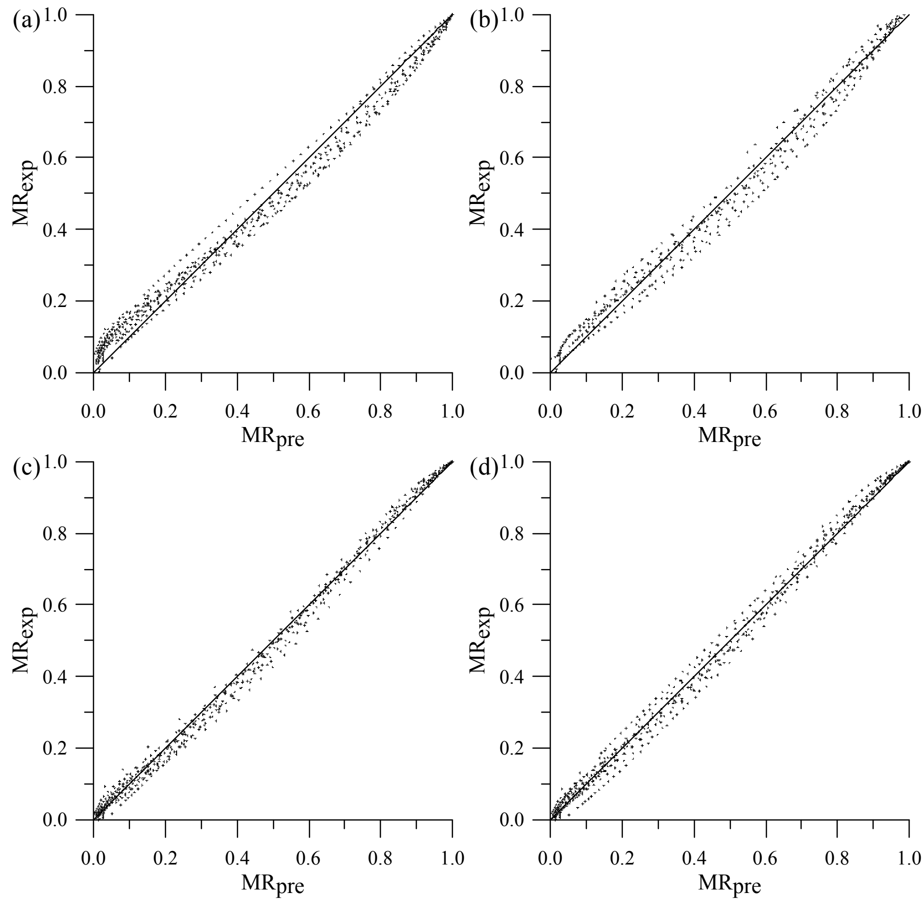

Fig. 2. Comparison of experimental and predicted moisture ratios by: (a) Lewis (Newton) model, (b) Henderson and Pabis model, (c) Page model, (d) Modified Page model (all of the discussed models have an appropriate parameter equation from Table 4).

CONCLUSIONS

1. It appears that the effect of vegetable species, drying air temperature, and slice thickness on the model (Lewis (Newton), Henderson and Pabis, Page, Modified Page, Wang and Singh) parameters can be taken into account individually.

2. All models, except that developed by Wang and Singh, with the parameters calculated considering the effect of temperature, slice thickness, and vegetable species may be applied to describe the drying kinetics of carrot, parsley, and red beetroos and onios slices of 5 and 10 mm thickness in the temperature range of 50-70°C.

3. The Page model with the parameters evaluated using a summation equation and square type dependence for drying air temperature and a rational one for slice thickness may be considered to be the most adequate (R^2=0.9699, *RMSE*=0.0587, χ^2=0.0035, *t*-stat=0.6739).

Conflict of interest: The authors declare that they have no conflict of interest.

Compliance with Ethical Requirements: This study does not contain any experiment involving human or animal subjects.

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