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Some Aspects of the Modelling of Dried Red Beets Rehydration Process

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Abstract: Some dehydrated products must be rehydrated before consumption or further industry processing. Optimization of the rehydration process needs mathematical models of the process. Despite the widespread use of computers and their associated software, empirical equations are still widely used in view of their simplicity and ease of computation. The mathematical description of the kinetics of mass gain, volume increase, dry matter loss, and moisture content increase and changes of rehydration indices during the rehydration of dried red beets was investigated. The effects of drying air temperature (T_d), drying air velocity (v_d), characteristic dimension (L), and rehydration temperature (T_r) on model constants were also examined. Red beets cubes (10 mm) and slices (5 and 10 mm) were dried in natural convection (v_d = 0.01 m/s), forced convection (v_d = 2 m/s), and fluidization (v_d = 6 m/s) at T_d = 50, 60, and 70 °C. The rehydration was conducted in distilled water at T_r = 20, 45, and 70 °C. The kinetics of rehydrating dried red beets was modelled applying five empirical models: Peleg, Lewis (Newton), Henderson–Pabis, Page, and modified Page. Equations were developed to make the model constants dependent on T_d, v_d, L, and T_r. Artificial neural networks (ANNs) (feedforward multilayer perceptron) were adopted to condition the rehydration indices on T_d, v_d, L, and T_r. The following models can be recommended as the most acceptable: (1) the modified Page model for mass gain (RMSE = 0.0236–0.0897) and for volume increase (RMSE = 0.0213–0.0972), (2) the Peleg model for dry mass loss (RMSE = 0.0161–0.610), and (3) the Henderson–Pabis model for moisture content increase (RMSE = 0.0350–0.1062). The ANNs performed the rehydration indices in an acceptable way (RMSE = 0.0528–0.2285). Both the rehydration indices and model constants depended (but to a different degree) on the investigated drying and rehydration conditions.

Keywords: rehydration; red beet; quality; mathematical model; ANN

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1. Introduction

Fruits and vegetables belong to the richest sources of bioactive compounds [1]. In the course of these products' consumption, we supply our organism with not only fibers, minerals, vitamins but also betamines, polyphenols or carotenoids. It has been proven that eating habits can lower the risk of such metabolic diseases as diabetes, obesity and also chronic inflammation, arthritic, hypertension, cardiovascular diseases, and cancers [2–5].

Red beet (*Beta vulgaris* L. ssp. *vulgaris*) derives from the region of the Mediterranean sea and belongs to the plant family Chenopodiaceae. It is cultivated in many parts of the world. Red beet is widely grown in Poland. The area under cultivation in 2021 was approximately 7.4 thousand hectares (4.5% of the total area of field vegetables cultivation), and the red beet harvest amounted to 324 thousand tons (about 6.2% of the total harvest of field vegetables) [6]. Red beet is considered one of the ten most potent vegetables with respect to its total phenolic content. Edible roots of red beets contain 4 to 12% sugar, 1.5% protein, 0.1% fat, and 0.8% fiber as well as vitamins such as B (B_1, B_2, B_3, B_6) and C. Red

beets are also source of calcium, copper, iron, magnesium, phosphorus, potassium, and sodium. They are rich in a water-soluble nitrogenous pigments (betacyanins) giving red beets their reddish-purple hue. These bioactive compounds have an antioxidant capacity and therefore are very good for human health. Betanin represents 75–78% of the betacyanin pigments content [7–9]. The green leafy part of red beets contains βcarotene and more iron than spinach [10]. The roots of red beets can be consumed fresh or after such processes as cooking, drying, the rehydration of dried products or fermentation. Pickled red beets are a traditional food in South America, and they are popular in Australia and New Zealand. Dried beetroots consumed as a chips can be rich in trans fatty acids and act as a counterbalance for traditional snacks. They are also a component of instant food. The juice from red beets (the composition of which is similar to raw ones) is a recommended healthy drink [11,12]. Beetroot power produced via belt/tray or spray drying or extracted pigments are industrially applicated as a natural red colorant in jellies, yoghurts, sweets, jams, breakfast cereals, dry mixes as soups or Indian curry mixes [13,14]. Red beets have medical uses because they are rich source of betamines. These pigments are reported to be antioxidants, compounds that delay the process of oxidation. Therefore, regularly consuming beetroots can protect against cardiovascular diseases, oxidative stress-related diseases and cancers and improve blood quality and digestion [7,14,15].

Red beets, in comparison to almost all other fruits and vegetables, have a short harvest period. Drying enables their longer shelf life by lowering their moisture content to such a level at which the deterioration of chemical reactions and microbiological contamination are minimalized to a safe level. Nowadays, the drying of fruits and vegetables is especially important because these dried products are added to ready-to-eat high nutrition meals and are ready supplements in food processing [16,17]. Because of this, plenty of dried fruits and vegetables have to be rehydrated to return to a state similar to fresh products. The reconstituting ability of dried food products depends, to a high degree, on their internal structure. The kinetics of rehydration and the worsening of quality characteristics of rehydrated product depend on the structural changes caused by predrying treatments, drying, and rehydration [18,19].

The drying and rehydration of red beets have not been investigated widely and not much data, especially about their rehydration, can be found in the literature. Shynkaryk et al. [20] studied the effects of pulsed electric fields (200–600 V/cm) and temperature (30–90 °C) on the convective drying of red beets. It was stated that this method of pretreatment caused greater tissue shrinkage (the smallest shrinkage for the untreated tissue), and therefore, the rehydration time was longer (the characteristic rehydration time is defined as the time required for the dimensionless ratio of the soluble matter contents of juice to attain one-half of its maximal value). Kaleta and Górnicki [21] investigated the effect of the particle shape and size of beetroots and the effect of the initial material load on convective drying kinetics. The drying course was modelled using theoretical and empirical models. Figiel [11] dried red beets using the following methods: convective drying, convective predrying and then vacuum microwave drying (VMD), and freeze drying. It was stated that the total time of the combined drying can be considerably shortened by the early use of VMD at a high microwave wattage. It turned out from the research that samples dried via both the second and third methods exhibited lower shrinkage, a better degree of rehydration and higher antioxidant activity than samples dried via convection. Gokhale and Lele [13] optimized the convective drying of the beetroots pulp with the objective of obtaining the maximum color retention. The drying process was modelled using empirical models. The quality of red beets power was characterized by the rehydration ratio and color. Hung and Duy [22] investigated the effect of drying methods (freeze-drying and heat-drying) on the bioactive compounds of vegetables, including red beets. Azam et al. [23] studied the drying of beetroots via the following methods: sun and shade drying, solar cabinet drying, and hot air tray drying. They stated that increasing the drying air temperature negatively influenced the rehydration ratio, the shrinkage ratio, and the color. Kumar et al. [9] showed that the microwave-assisted fluidized bed drying of red beets gave

a lower drying time and lower final moisture content than fluidized bed drying. Vallespir et al. [24] modelled the effective coefficient of moisture diffusion during the drying of beetroots applying finite elements. Freezing pretreatment and the application of ultrasound on convective drying [24] and freezing [25] have also been investigated. Dirim et al. [26] studied the effect of microwave power on the drying kinetics of the red beets' puree in the microwave oven, and Kerr and Varner [27] studied the vacuum belt dehydration of chopped red beetroots. The drying course was modelled applying theoretical and empirical models. Liu at al. [28] investigated the influence of different drying methods on the quality of dried beetroots. The obtained results showed that microwave vacuum drying and microwave drying were superior to vacuum drying, heat pump drying, and freeze drying in terms of drying time. Beetroots dried via microwave vacuum drying had the largest rehydration ratio, whereas the lowest ratio was obtained via microwave drying.

To predict the dried vegetables and fruit behavior of the rehydration process, theoretical models, empirical models, and machine learning techniques are used, and despite the widespread use of computers and their associated software, empirical equations are still widely used in view of their simplicity and ease of computation. Theoretical models are based on the general theory of heat and mass transfer laws and their parameters have physical meaning, but these models are more difficult in application compared to empirical models, and the constants of empirical models can inform us about the described process rate.

As can be seen from the literature, there is little information concerning the modelling of the rehydration of dried red beets. Therefore, the present investigations were conducted with the following aims:

- Mathematical description of the kinetics of mass gain, volume increase, dry matter loss, and moisture content increase and changes in rehydration indices during the rehydration of dried red beets;
- Adoption of the empirical models applied in the literature and artificial neural networks for rehydration modelling;
- Formulating equations to determine the constants of used rehydration models;
- Examination of the effects of the drying air temperature (T_d), the velocity (v_d), the characteristic dimension (L) and rehydration temperature (T_r) on the kinetics of mass gain, volume increase, dry matter loss, and moisture content increase and changes in rehydration indices during the rehydration of dried red beets.

Although models from the literature were used for modelling, the constants of these models can be calculated from formulated equations (drying and rehydration parameters are the variables for these equation). In this way, it is possible to predict the course of the rehydration process for the drying and rehydration parameters other than those analyzed and to optimize these processes, which can be used in industry. Optimization, using the developed models of the rehydration process, will allow, among other aspects, to determine the parameters of the drying and rehydration processes at which the obtained rehydrated matter will be characterized by specific features, e.g., a large amount of substance (dry matter) penetrating into the rehydrating water (red beet juice).

2. Materials and Methods

Fresh red beets (variety Wodan F1) were procured from one producer, and they dated from one harvest. Before drying, the roots were washed with fresh water and, after removing the excess surface water, peeled, cut into pieces (Table 1) with cutting machine, and dried (on some day).

Table 1. Conditions for conducting drying and rehydration processes.

Process	Parameter	Values
Drying	particle size and dimension	10 mm thick cubes 5 and 10 mm thick slices
	method of drying and drying air velocity v_d	natural convection (chamber dryer), 0.01 m/s forced convection (tunnel dryer), 2 m/s fluid bed drying (laboratory fluidized bed dryer), 6 m/s
	drying air temperature T_d	50 °C, 60 °C, 70 °C
Rehydration	temperature of distilled water T_r	20 °C, 45 °C, 70 °C

According to Pabis et al. [29], the red beet characteristic dimension was calculated as follows:

- For slices having a thickness of 2s: $L = s$,
- For cubes having a thickness of 2s: $L^{-2} = 3s^{-2}$.

The initial moisture content of the fresh roots was approx. 91% w.b. (10.1 d.b.), and for the dried ones, it was about 9% w.b. (0.1 d.b.).

The conditions of the drying experiments are shown in Table 1. The dryers (chamber dryer, tunnel dryer, and fluidized bed dryer) are located in the Department of Fundamentals of Engineering and Power Engineering, Warsaw University of Life Sciences, Warsaw, Poland. The applied equipment and the way of conducting the experiments have been reported in details in our previous papers [21,30,31]. Dried samples (the same drying conditions, three independent experiments) were mixed and next stored in a sealed vessel for about seven days (20 °C).

The conditions of conducting the rehydration process and procedure are presented in Tables 1 and 2. The mass of dried red beets taken for the rehydration was approx. 10 g. The distilled water was static, and its temperature (20, 45, and 70 °C) was constant during the experiment. A red-beets-to-water ratio of 1:20 (w/w) was used (at the beginning of the rehydration process). The mass of the rehydrated sample m was determined with scales (WPE 300, RADWAG, Radom, Poland, with ±0.001 g accuracy), whereas dry matter changes in dried red beets $m_{d.m.}$ during rehydration were determined via the AOAC method [32]. The change in sample volume V was measured using the buoyancy method (in petroleum benzene) [33] (relative error < 5%). All experiments were carried out in triplicate.

Table 2. Rehydration procedure.

Temperature of Distilled Water T_r, °C	Time of Mass, Dry Matter, and Volume Determination, min
20	0, 10, 20, 40, 90, 180, 360
45	0, 20, 40, 60, 90, 150, 300
70	0, 10, 20, 40, 60, 120, 240

Five empirical models applied for describing the kinetics of the rehydration of dried red beets are given in Table 3. Such models were employed because their constants have physical meaning (they inform us about the rate of the considered process).

The following nomenclature is used for the models shown in Table 3: t is the time (h), and A_1, A_2, a, k, and n are the constants.

According to measured value, the variable X means the following ratios: rehydrated particles mass to the mass of dried particles taken for rehydration (m/m_0), rehydrated particles volume to the volume of dried particles taken for rehydration (V/V_0), rehydrated particles dry matter to the dry matter of dried particles taken for rehydration ($m_{d.m.}/m_{d.m.0}$), and rehydrated particles moisture content to the moisture content of dried particles taken for rehydration (M/M_0).

Table 3. Empirical models used for describing the course of the rehydration of dried red beets.

Model No.	Model Equation	Model Name	References
(1)	$Y = 1 \pm \frac{t}{A_1 + A_2 t}$ *	Peleg	[34]
(2)	$Y = \exp(-kt)$	Lewis (Newton)	[35]
(3)	$Y = a\exp(-kt)$	Henderson–Pabis	[36]
(4)	$Y = \exp(-kt^n)$	Page	[37]
(5)	$Y = \exp(-(kt)^n)$	Modified Page	[38]

* Sign minus refers to the dry matter of solid loss.

The moisture content (dry basis) is determined according to formula

$$M = \frac{m - m_{d.m.}}{m_{d.m.}} \tag{6}$$

Variable Y is calculated for the mass gain and volume increase using equation

$$Y = \frac{X - 1}{X_e - 1} \tag{7}$$

and for dry matter loss, the formula is

$$Y = X \tag{8}$$

Equilibrium value X_e is evaluated from the Peleg model assuming that the rehydration lasted long enough ($t \to \infty$)

$$X_e = 1 \pm \frac{1}{A_2} \tag{9}$$

The Peleg model was formulated for describing the process of rehydration. Although it is empirical model, its constants have physical meaning. Constant A_1 gives the information about the water absorption rate especially during the early stage of the discussed process. Constant A_2 allows us to predict the maximum capacity of water absorption. The mentioned model has been widely applied to predict the rehydration course of dried biological materials [39–44].

Empirical models (2)–(5) given in Table 3 were formulated for describing the drying process. Their constant k also has a physical meaning because it gives information about the rate of the investigated process. The discussed models have been, however, applied also for describing the course of dried material rehydration. A first-order kinetics model, otherwise known as the Lewis (Newton) model, has been adopted to predict the rehydration process of such food materials as carrots [45], date plums [46], ginger [47], mangoes [48], onions [49], pumpkins [50], soybeans [51] and tomatoes [52]. The Page model has been used to describe the rewetting kinetics of such dried products as canola [53], lemon [54], pineapple [55], rough rice [56], Thompson seedless grape [54], and tiger nut [57]. The Henderson–Pabis and the modified Page models have been used to predict the course of the rehydration of dried apples [58].

Obtained from experiments, rehydration data (for dried red beet) were fitted to five investigated models (presented in Table 3). The Matlab R2018a software with the Levenberg–Marquardt algorithm was applied (Curve Fitting Toolbox2018a, MathWorks, Inc., Natick, MA, USA), whereas the quality of the considered models was statistically determined using the coefficient of determination R^2, adjusted R^2, and root mean square error RMSE (the highest values of R^2 and adjusted R^2 and the lowest RMSE values indicate the model with the best fit) [40,59,60].

In order to investigate the effect of drying and rehydration conditions on the constants of models (1)–(5), the following type of equation was used:

$$\text{Constant} = a_0 + a_1 T_d + a_2 v_d + a_3 L + a_4 T_r + a_5 {T_d}^2 + a_6 {v_d}^2 + a_7 L^2 + a_8 {T_r}^2 + a_9 T_d v_d + a_{10} T_d L + a_{11} T_d T_r + a_{12} v_d L + a_{13} v_d T_r + a_{14} L T_r \tag{10}$$

where $a_0 \div a_{14}$ are constants, L is the characteristics dimension, T_d is the drying air temperature, T_r is the rehydration temperature, and v_d is the drying air velocity. The statistical analysis ANOVA was applied.

The rehydration capacity of the dried red beet was determined using the following indices:

- Rehydration index RI:

$$\mathrm{RI} = \frac{\text{mass of material after rehydration}}{\text{mass of dried material}} \tag{11}$$

The discussed index is very often applied for describing rehydration. It has been used to characterize the rehydration of apples [61], Asian pear [62], banana crisps [63], bitter melon [64], celery [65], quince [66], and sea cucumber [67].

- Water absorption capacity WAC:

$$\mathrm{WAC} = \frac{m_r(100 - s_r) - m_d(100 - s_d)}{m_0(100 - s_0) - m_d(100 - s_d)} \tag{12}$$

where m is the mass in kg, s is the dry matter content in %, and subscripts d, 0, and r refer to dry, before drying, and rehydrated, respectively.

The discussed index has been accepted as a quality indicator for rehydrated mango [68], potatoes [69], squid fillets [70], and tomatoes [71].

The feedforward multilayer perceptron (MLP) artificial neural networks (ANNs) (Neural Network Toolbox 2018a, MathWorks, Inc., Natick, MA, USA) were used to predict both considered rehydration indices: RI and WAC. The inputs were T_d, v_d, T_r and L, and the outputs were RI, WAC, and both RI and WAC together. The inputs and outputs were normalized in order to receive values within the range 0–1 using the min–max method. The cases were randomly divided into following sets: testing (15% cases), training (70%), and validation (15%), whereas the quality of the applied model was determined with the R^2 and RMSE.

ANNs were used in the literature for the description of rehydration indexes [72] and the optimization of rehydration processes [73] (dried apples).

3. Results and Discussion

Table 4 presents the results of the statistical analysis on the modelling of mass, volume, dry matter, and moisture content changes during the rehydration of dried red beets. As far as mass gain during the rehydration of dried red beets is concerned, it can be stated that all models described the mass gain in a quite acceptable way. The values of used statistical test criteria for the five considered models varied between 0.9069 and 0.9967 for R^2, 0.9020 and 0.9964 for adjusted R^2, and 0.0179 and 0.2388 for RMSE. The lowest values of R^2 and adjusted R^2 were present in the Lewis (Newton) model and Henderson and Pabis model (0.9069–0.9852 and 0.9020–0.9845, respectively), but the mentioned models showed better values regarding the root mean square error (0.0383–0.1075) than the Peleg model (0.1078–0.2388) for which the values of R^2 and adjusted R^2 ranged from 0.9659 to 0.9950 and from 0.9642 to 0.9948, respectively. The Page and the modified Page models described the kinetics of dried red beet's mass gain during rehydration in the best way. The values of the used statistical test methods were as follows: R^2 = 0.9687–0.9967, adjusted R^2 = 0.9671–0.9964, and RMSE = 0.0179–0.0528.

The conclusions drawn from the statistical analyses on the modelling of volume increase were similar to the question of mass gain. It can be accepted that all models fitted quite well to the experimental data for volume increase. The results for the statistical analyses for all considered models were the following: R^2 = 0.8885–0.9950, adjusted R^2 = 0.8826–0.9947, and RMSE = 0.0210–0.4080. The Page model and the modified Page model showed, however, the best values of the considered statistical criteria, namely, 0.9444–0.9950 for the coefficient of determination, 0.9414–0.9947 for the adjusted coefficient of determination, and 0.0210–0.0877 for the root mean square error. Therefore, both models

can be recommended as the most suitable for the modelling of the course of volume increase during the rehydration process for dried red beets.

Table 4. Results of statistical analyses on the modelling of m, V, $m_{d.m.}$, and M changes during the rehydration of dried red beets.

Model No.	Model Name	Variable	R^2	Adjusted R^2	RMSE
(1)	Peleg	mass gain	0.9659–0.9950	0.9642–0.9948	0.1078–0.2388
		volume increase	0.9326–0.9917	0.9290–0.9913	0.1434–0.4080
		dry matter loss	0.9400–0.9947	0.9368–0.9944	0.0135–0.0362
		moisture content increase	0.9402–0.9934	0.9370–0.9931	2.5976–5.6206
(2)	Lewis (Newton)	mass gain	0.9194–0.9852	0.9151–0.9845	0.0413–0.1075
		volume increase	0.9108–0.9837	0.9061–0.9829	0.0523–0.1163
		dry matter loss	0.9371–0.9898	0.9338–0.9893	0.0343–0.0986
		moisture content increase	0.9385–0.9927	0.9353–0.9924	0.0304–0.6950
(3)	Henderson–Pabis	mass gain	0.9069–0.9846	0.9020–0.9837	0.0383–0.0952
		volume increase	0.8885–0.9814	0.8826–0.9804	0.0495–0.1037
		dry matter loss	0.9321–0.9893	0.9285–0.9887	0.0335–0.0895
		moisture content increase	0.9390–0.9930	0.9358–0.9926	0.0282–0.0746
(4)	Page	mass gain	0.9687–0.9967	0.9671–0.9964	0.0179–0.0528
		volume increase	0.9444–0.9950	0.9414–0.9947	0.2010–0.0656
		dry matter loss	0.9390–0.9965	0.9358–0.9963	0.1098–0.0762
		moisture content increase	0.9380–0.9931	0.9347–0.9928	0.0267–0.0693
(5)	Modified Page	mass gain	0.9687–0.9966	0.9671–0.9964	0.0179–0.0528
		volume increase	0.9444–9.9950	0.9414–0.9947	0.0210–0.0877
		dry matter loss	0.9390–0.9965	0.9358–0.9963	0.0198–0.0762
		moisture content increase	0.9643–0.9931	0.9625–0.9928	0.0267–0.0603

As far as dry matter loss during the rehydration of dried red beets is concerned, it can be noticed that all models described the kinetics of dry matter changes during the considered process satisfactorily. The R^2 fell within the range of 0.9321 to 0.9965, the adjusted R^2 changed from 0.9285 to 0.9963, and the RMSE varied between 0.0135 and 0.986. Comparing the results of the statistical analyses for the five considered models, the Peleg model can be treated as the best among them (R^2 = 0.9400–0.9947, adjusted R^2 = 0.9368–0.9944, and RMSE = 0.0135–0.0362).

Taking into account the values of the determination coefficient (0.9380–0.9934) and the values of the adjusted determination coefficient (0.9347–0.9931), it can be assumed that all considered models performed well regarding the moisture content increase during the rehydration process for dried red beets. The values of the RMSE for the Page model (2.5976–5.6206) were, however, much higher than for the remaining models (0.267–0.0746). Comparing the results of the statistical analyses, it can be stated that the most acceptable values of the considered test methods were obtained from the modified Page model (R^2 = 0.9643–0.9931, adjusted R^2 = 0.9625–0.9928, RMSE = 0.0267–0.0603).

Our results for the rehydration process modelling have been similar to those previously presented [45–47,50,74,75].

The results of examining the impact of T_d, v_d, L, and T_r on the constants of the investigated models are presented in Table 5 for the models adopted to predict the mass gain during the rehydration of dried red beets, in Table 6 for the models adopted to volume increase, in Table 7 for the models adopted to dry matter loss, and in Table 8 for the models adopted to moisture content increase. As can be seen from Table 5, the rehydration rate constants k for the Lewis (Newton) model, the Henderson–Pabis model, the Page model, and the modified Page model adopted to mass gain depended (in a statistically significant way) on all drying and rehydration conditions taken into account: T_d, v_d, L, and T_r. The same situation was noticed for parameter a in the Henderson–Pabis model and for parameters n in the Page and modified Page models. These parameters depended

(in a statistically significant way) on T_d, v_d, L, and T_r. Parameter A_1 of the Peleg model depended (in a statistically significant way) on drying and rehydration conditions: T_d, v_d, L, and T_r. However, the dependence of parameter A_2 on the rehydration temperature was statistically insignificant. Summing up, the five considered models enabled the prediction of mass gain during the rehydration of dried red beets, taking into account such conditions for drying and rehydration as T_d, v_d, L, and T_r.

Table 5. Parameter equations for the models adopted to m changes during rehydration of dried red beets.

Model No.	Model Name	Parameter Equation
(1)	Peleg	$A_1 = 0.53319{v_d}^2 - 0.0655T_dv_d + 0.1076T_dL - 0.0603LT_r$ $A_2 = -0.952 + 0.68791L + 0.00142{v_d}^2 - 0.0892L^2 - 0.0001T_dv_d$
(2)	Lewis (Newton)	$k = 0.00028T_d + 0.00565v_d + 0.00376L - 0.0006{v_d}^2 + 3.1 \times 10^{-6}{T_r}^2 - 10^{-4}T_dL - 0.0006v_dL$
(3)	Henderson–Pabis	$k = 0.01115 + 0.00224v_d - 0.0003{v_d}^2 - 4 \times 10^{-5}T_dL + 4.2 \times 10^{-6}T_dT_r$ $a = -0.0191v_d + 0.49871L + 0.00221{v_d}^2 - 0.0651L^2 - 5 \times 10^{-5}{T_r}^2 + 6.9 \times 10^{-5}T_dT_r$
(4)	Page	$k = 0.03324v_d - 0.0035{v_d}^2 - 4 \times 10^{-5}{T_r}^2 - 0.0003T_dL + 8.3 \times 10^{-5}T_dT_r$ $n = 0.64387 - 0.08v_d + 0.00943{v_d}^2 + 0.00074T_dL - 3 \times 10^{-5}T_dT_r$
(5)	Modified Page	$k = 0.00361v_d + 0.00786L - 0.0005{v_d}^2 - 0.001L^2 - 5 \times 10^{-5}T_dL + 4.9 \times 10^{-6}T_dT_r$ $n = 0.70781 - 0.0011T_d - 0.0854v_d + 0.01119{v_d}^2 + 0.00075T_dL - 3 \times 10^{-5}T_dT_r$

Table 6. Parameter equations for the models adopted to volume changes during rehydration of dried red beets.

Model No.	Model Name	Parameter Equation
(1)	Peleg	$A_1 = -0.61102v_d + 4.35955L - 0.0423LT_r$ $A_2 = 0.00055{v_d}^2 - 0.0097L^2 + 0.00151T_dL$
(2)	Lewis (Newton)	$k = 0.00872v_d + 6.1 \times 10^{-6}{T_d}^2 - 0.0004\,{v_d}^2 + 2.9 \times 10^{-6}{T_r}^2 - 10^{-4}T_dv_d - 6 \times 10^{-5}T_dL$
(3)	Henderson–Pabis	$k = 4.1 \times 10^{-5}T_dv_d + 9.6 \times 10^{-6}T_dT_r - 5 \times 10^{-5}v_dT_r - 6 \times 10^{-5}LT_r$ $a = 0.92777 - 0.0019T_d - 0.0046v_d - 6 \times 10^{-5}{T_r}^2 + 8.6 \times 10^{-5}T_dT_r$
(4)	Page	$k = 0.05908 + 0.03112v_d - 0.0032{v_d}^2 - 0.0003T_dL + 2.6 \times 10^{-5}T_dT_r$ $n = -0.0514v_d + 0.38982L + 0.00646{v_d}^2 - 0.049L^2 - 2 \times 10^{-5}{T_r}^2$
(5)	Modified Page	$k = 0.00028T_d + 0.00295v_d - 0.0004{v_d}^2 - 5 \times 10^{-5}T_dL + 3.7 \times 10^{-6}T_dT_r$ $n = -0.056v_d + 0.39677L + 0.007{v_d}^2 - 0.05L^2 - 2 \times 10^{-5}{T_r}^2$

Table 7. Parameter equations for the models adopted to dry matter changes during rehydration of dried red beets.

Model No.	Model Name	Parameter Equation
(1)	Peleg	$A_1 = 355.113 - 6.996T_d - 91.017L + 1.46026{v_d}^2 + 0.01411\,{T_r}^2 + 2.64528T_dL - 5.2259\,v_dL - 0.7968LT_r$ $A_2 = -12.927 + 0.00792T_d + 0.04094v_d + 8.57966L - 0.0077{v_d}^2 - 1.1362L^2 + 0.00014{T_r}^2 - 0.0002T_dT_r$
(2)	Lewis (Newton)	$k = 0.00028T_d + 0.00688v_d + 0.0008{v_d}^2 + 1.2 \times 10^{-6}{T_r}^2 - 0.00002LT_r$
(3)	Henderson–Pabis	$k = 0.01533 + 0.00624v_d - 0.0008{v_d}^2 + 1.2 \times 10^{-5}{T_r}^2 - 0.0001LT_r$ $a = 2.03326 - 0.6471L + 0.08638L^2 - 0.0046\,v_dL^2 + 0.00028v_dT_r$
(4)	Page	$k = 0.00157T_d - 0.0003T_dL + 1.7 \times 10^{-5}T_dT_r + 0.00035\,v_dT_r$ $n = 0.6762 + 0.00538L^2 - 0.0094v_dL$
(5)	Modified Page	$k = 0.01813v_d + 0.00517L - 0.0014{v_d}^2 + 1.5 \times 10^{-5}{T_r}^2 - 0.0029v_dL - 0.0002LT_r$ $n = 0.04846v_d + 0.38198L - 0.0421L^2 - 0.0266v_dL$

Table 8. Parameter equations for the models adopted to changes of moisture content during rehydration of dried red beets.

Model No.	Model Name	Parameter Equation
(1)	Peleg	$A_1 = 0.03954{v_d}^2 + 0.0004{T_r}^2 - 0.005T_d v_d + 0.01231T_d L - 0.0004T_d T_r - 0.0089LT_r$ $A_2 = -0.103 + 0.06538L - 0.0086L^2$
(2)	Lewis (Newton)	$k = 0.00012T_d + 0.0065v_d - 0.0006{v_d}^2 + 3.4 \times 10^{-6}{T_r}^2 - 0.001v_d L - 2 \times 10^{-5}LT_r$
(3)	Henderson–Pabis	$k = 0.00229v_d + 0.005L - 0.0004{v_d}^2 - 0.0009L^2 + 2.3 \times 10^{-6}{T_r}^2$ $a = 2.38536 - 0.0174v_d - 0.8424L + 0.00209{v_d}^2 + 0.11246L^2$
(4)	Page	$k = -0.6793 + 0.01179v_d + 0.41076L - 0.0014{v_d}^2 - 0.0547L^2 + 1.2 \times 10^{-5}{T_r}^2 - 0.0001LT_r$ $n = 5.83176 - 2.9365L + 0.00611{v_d}^2 + 0.39838L^2 - 3 \times 10^{-5}T_d T_r - 0.0218v_d L$
(5)	Modified Page	$k = 0.00013v_d + 0.00861L - 0.0014L^2$ $n = 0.8561 - 0.0269v_d + 0.00401L^2 - 10^{-5}{T_r}^2$

The rehydration rate constants k for four of the considered models used for the description of volume increase (Table 6) depended (in a statistically significant way) on all investigated parameters: T_d, v_d, L, T_r. The dependence of parameter a (for the Henderson–Pabis model) on the characteristic dimension was statistically insignificant, and for parameter n (in the Page model and modified Page model), the influence of the drying air temperature was statistically insignificant. Parameter A_1 for the Peleg model depended, in a statistically significant way, on v_d, L, T_r, whereas the dependence of the parameter A_2 on the rehydration temperature was statistically insignificant. To summarise, all investigated models allowed for the prediction of the kinetics of volume increase in the rehydration process for dried red beets considering the drying air temperature and velocity, characteristic dimension, and rehydration temperature.

It appeared, from Table 7, that the parameters A_1 and A_2 for the Peleg model and parameters k for the Lewis (Newton) and Page models adopted to describe the course of dry matter loss during the rehydration of dried red beets depended, in a statistically significant way, on T_d, v_d, L, and T_r. The dependence of parameter n, for the Peleg model, on both the drying air temperature and rehydration temperature was statistically insignificant. Both parameters k and a for the Henderson–Pabis model were statistically insignificant on drying air temperature. As far as the modified Page model was considered, its parameter k did not depend, in a statistically significant manner, on T_d, whereas its parameter n was dependent, in a statistically significant way, on v_d and L. It can be stated, due to the discussed relationship, that if there is a need to predict the course of dry matter loss during the rehydration of dried red beets, whilst taking into consideration the influence of all the investigated parameters of drying and rehydration processes (T_d, v_d, L, T_r), the Peleg model, Lewis model and Page model should be chosen. If, however, the drying air temperature is not so important for prediction, the Henderson–Pabis model and modified Page model could be applied as well.

It is shown in Table 8 that parameter A_1 for the Peleg model, the rehydration rate constant k for the Lewis model and parameter n for the Page model, applied to characterize the moisture content increase during the rehydration of dried red beets, depended, in a statistically significant way, on all drying and rehydration conditions taken into account, namely, T_d, v_d, L, T_r. The dependence of the rehydration rate constant k, for the Henderson–Pabis and Peleg models, on the drying air temperature was statistically insignificant, whereas the dependence of parameter a (in the Henderson–Pabis model) on both the drying and rehydration temperatures was statistically insignificant. As far as the modified Page model was concerned, its parameter k depended, in statistically significant manner, on the drying air velocity and characteristics dimension, whereas its parameter n depended on drying air temperature in a statistically insignificant manner. Parameter A_2 for the Peleg model depended, in a statistically significant way, only on the characteristics dimension. Summing up this discussion, it can be said that three of the considered models, namely

Peleg, Lewis (Newton), and Page, enabled the prediction of the moisture content increase during the rehydration of dried red beets, considering the influence of T_d, v_d, L, and T_r. The Henderson–Pabis model and modified Page models can be adopted for prediction only when the drying air temperature is not very important for the prediction for the investigated process.

Table 9 shows the results of statistical analyses on the modelling of mass, volume, dry matter, and moisture content changes in the dried red beets during rehydration, where model parameters are expressed with equations presented in Tables 5–8. As far as the mass gain during the rehydration of dried red beets is concerned, it can be suggested that the Lewis (Newton), Henderson–Pabis, and modified Page models fitted quite well to the experimental data for mass gain. The values of the applied statistical test criteria for the three mentioned models ranged from 0.9070 to 0.9966 for R^2, from 0.9021 to 0.9964 for adjusted R^2, and from 0.0236 to 0.1076 for RMSE. It can be noticed, however, that among the discussed models, the modified Page model gave the best values out of the considered test methods (R^2 = 0.9647–0.9966, adjusted R^2 = 0.9628–0.9964, RMSE = 0.0236–0.0897), and therefore, it can be recommended as the most acceptable for describing mass gain kinetics during the rehydration of dried red beets.

Table 9. Summary of the results of statistical analyses on the modelling of m, V, $m_{d.m.}$, and M changes during the rehydration of dried red beets at models parameters expressed with equations presented in Tables 5–8.

Model No.	Model Name	Variable	R^2	Adjusted R^2	RMSE
(1)	Peleg	mass gain	0.7248–0.9926	0.7103–0.9922	0.1329–1.3085
		volume increase	0.9175–0.9915	0.9131–0.9911	0.2194–1.1742
		dry matter loss	0.9381–0.9948	0.9348–0.9945	0.0161–0.0610
		moisture content increase	0.9076–0.9918	0.9027–0.9914	3.0062–18.0152
(2)	Lewis (Newton)	mass gain	0.9185–0.9850	0.9142–0.9842	0.0418–0.1076
		volume increase	0.8888–0.9758	0.8830–0.9745	0.0652–0.1466
		dry matter loss	0.9104–0.9899	0.9057–0.9893	0.0435–0.1684
		moisture content increase	0.9294–0.9907	0.9257–0.9902	0.0353–0.1015
(3)	Henderson–Pabis	mass gain	0.9070–0.9834	0.9021–0.9797	0.0392–0.0956
		volume increase	0.8556–0.9733	0.8480–0.9719	0.0564–0.1336
		dry matter loss	0.8702–0.9883	0.8634–0.9877	0.0449–0.1754
		moisture content increase	0.9400–0.9924	0.9368–0.9920	0.0350–0.1062
(4)	Page	mass gain	0.7849–0.9962	0.7736–0.9960	0.0219–3.0943
		volume increase	0.9113–0.9923	0.9066–0.9919	0.0365–0.8878
		dry matter loss	0.9373–0.9963	0.9340–0.9961	0.0209–0.1474
		moisture content increase	0.8327–0.9935	0.8239–0.9932	0.0282–1.4445
(5)	Modified Page	mass gain	0.9647–0.9966	0.9628–0.9964	0.0236–0.0897
		volume increase	0.9349–0.9948	0.9314–0.9945	0.0213–0.0972
		dry matter loss	0.6522–0.9898	0.6339–0.9892	0.0463–0.2967
		moisture content increase	0.9137–0.9919	0.9091–0.9915	0.0311–0.1913

It can be admitted that the Page, modified Page, and the Lewis models performed well regarding the volume increase. The values of the used statistical test methods changed from 0.8888 to 0.9948 for the R^2, from 0.8830 to 0.9945 for the adjusted R^2, and from 0.0213 to 0.8878 for the RMSE. Comparing the obtained results, it can be stated that the mentioned Page model gave the most acceptable results of the statistical analyses, as far as the volume increase during the rehydration of dried red beets is concerned (R^2 = 0.9349–0.9948, adjusted R^2 = 0.9314–0.9945, RMSE = 0.2213–0.0972).

Taking into account the values of R^2 (0.9104–0.9963), adjusted R^2 (0.9057–0.9961), and RMSE (0.0161–0.1684), it can be decided that three models, namely, Peleg, Lewis (Newton), and Page, described the course of dry matter loss during the rehydration of dried red

beets. The Peleg model gave, however, the best results (R^2 = 0.9381–0.9948, adjusted R^2 = 0.9348–0.9945, RMSE = 0.0161–0.0610).

As far as the moisture content increase during the investigated process is concerned, it can be accepted that the Lewis (Newton), Henderson–Pabis, and modified Page models described the kinetics of the process in quite acceptable ways. The values of the considered statistical test criteria for the mentioned models fell within the range of 0.9137 to 0.9924 for R^2, 0.9091 to 0.9920 for adjusted R^2, and 0.0311 to 0.1913 for RMSE. Comparing the obtained results, it can be admitted that among the three indicated models, the Henderson–Pabis model gave slightly better results in describing the moisture content increase during the rehydration of dried red beets (R^2 = 0.9400–0.9924, adjusted R^2 = 0.9368–0.9920, RMSE = 0.0350–0.1062).

The investigated models, namely, Lewis (Newton), Henderson–Pabis, Page, and modified Page, are empirical ones, but their constants have physical meaning because they give the information about the rate of the investigated process. It turned out, from research, that model constants depended on the parameters of drying and rehydration processes. Determined equations of the model constants (Tables 5–8) allowed us to calculate the values of these constants and to predict how the kinetics of the rehydration of dried red beets (mass gain, volume increase, dry matter loss, and moisture content increase) depends on drying and rehydration conditions, namely, on T_d, v_d, L, and T_r. Our results regarding the modelling of the rehydration process (model constants were calculated based on the parameters of the drying and rehydration conditions) were similar to those previously presented [75,76].

Different ANN structures were tested (Table 10). We chose the structures of ANNs that were uncomplicated and simultaneously characterized by appropriately good statistics. The RI and WAC were predicted applying artificial neural networks. MLP 4-4-1 was adopted for RI (Figure 1a) and MLP 4-4-1 for WAC (Figure 2a), whereas MLP 4-4-2 was adopted for both indices RI and WAC together (Figure 3a) with *logsig*

$$\mathrm{F(x)} = \frac{1}{1 + exp^{-\beta x}} \tag{13}$$

and *tagsig*

$$\mathrm{F(x)} = \frac{2}{1 + exp^{-\beta x}} - 1 \tag{14}$$

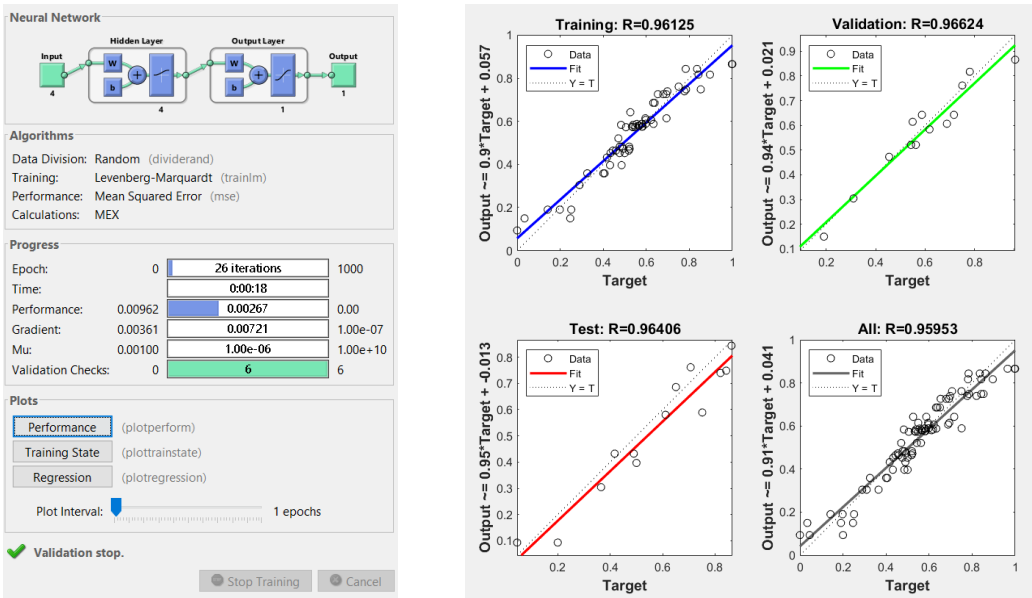
transfer functions in the hidden layer and the output layer, respectively. The *trainlm* (training) and *learngdm* (adaptation) functions were used. The ANN describing index RI gave the highest values of the correlation coefficient R for the validation set (R = 0.9662), for WAC, the discussed coefficient for the validation set equaled 0.9518, and for both indices RI and WAC together, the value of R = 0.9508. Table 11 presents the weights and biases (between the input and hidden layer and between the hidden and output layers) for indices RI, WAC, and both RI and WAC.

Table 12 presents the results of statistical analyses on the modelling of rehydration indices. As far as the coefficient of determination R^2 is concerned, the highest values were obtained for the ANNs describing both indices RI and WAC, and the values were as follows: R^2 = 0.9348 for RI, R^2 = 0.9327 for WAC, and R^2 = 0.9347 for RI and WAC. The values of R^2 for the networks describing the discussed indices separately were lower, namely, 0.9207 for RI and 0.9078 for WAC. The same situation was observed for the values of RMSE. The lowest, so the best values, were achieved for the neural networks describing both indices RI and WAC: RMSE = 0.0529 for RI, RMSE = 0.5049 for WAC, and RMSE = 0.0539 for RI and WAC. The network adopted for RI gave the values of RMSE equal to 0.5084, and as far as the network adopted for WAC is concerned, RMSE = 0.2285. It resulted from the investigations that the ANNs adopted to characterize both indices RI and WAC together can be recommended as the most suitable for the prediction of the behavior of discussed

rehydration indices. Our results regarding the modelling of rehydration indices using ANNs were similar to those previously presented [72,77].

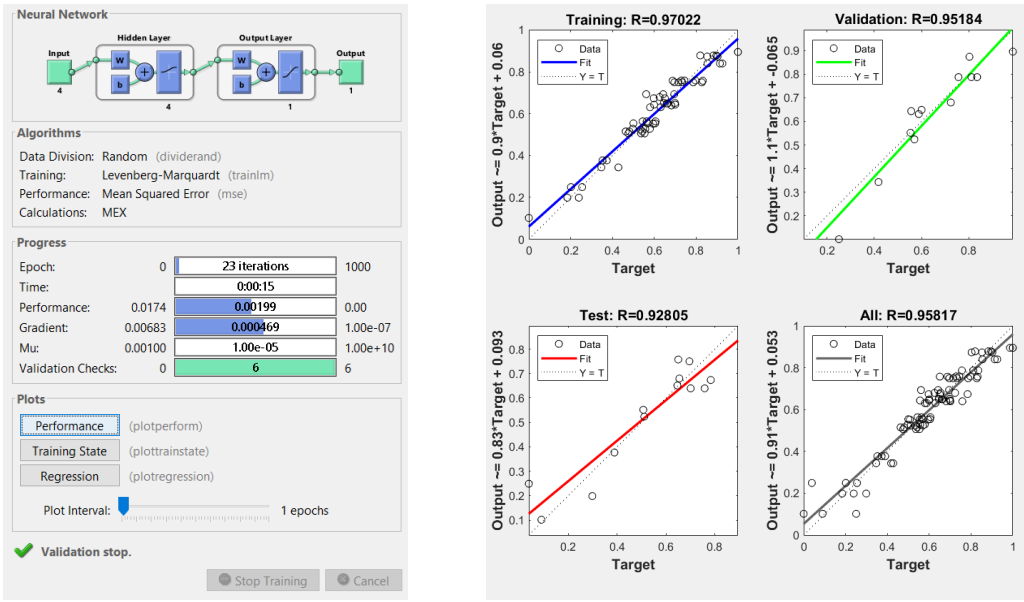
Table 10. ANN architectures tested.

ID.	Refer to	Activated Function in the Hidden Layer	Number of Neurons in the Hidden Layer	Activated Function in the Output Layer	R	
					Test	Validation
1	RI	*logsig*	3	*tagsig*	0.9634	0.9653
2			4		0.9641	0.9662
3			5		0.9641	0.9661
4	WAC		3		0.9168	0.9453
5			4		0.9281	0.9518
6			5		0.9283	0.9510
7	RI + WAC		3		0.9678	0.9453
8			4		0.9703	0.9501
9			5		0.9701	0.9502
10	RI	*logsig*	3	*pureline*	0.9535	0.9553
11			4		0.9546	0.9610
12			5		0.9450	0.9513
13	WAC		3		0.8699	0.9035
14			4		0.9041	0.9374
15			5		0.9134	0.9432
16	RI + WAC		3		0.9173	0.9214
17			4		0.9256	0.9311
18			5		0.9342	0.9421



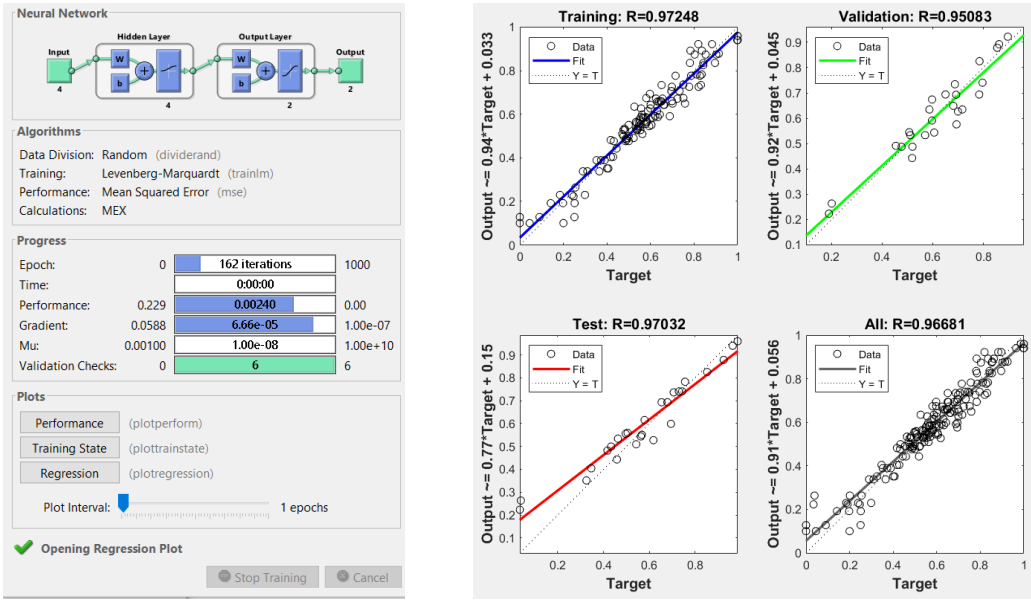
(**a**) (**b**)

Figure 1. The ANN structure and details of ANN training. (**a**) The goodness of fit of ANN, (**b**) for index RI (inputs: T_d, v_d, T_r and L).



(**a**) (**b**)

Figure 2. The ANN structure and details of ANN training. (**a**) The goodness of fit of ANN, (**b**) for index WAC (inputs: T_d, v_d, T_r and L).



(**a**) (**b**)

Figure 3. The ANN structure and details of ANN training. (**a**) The goodness of fit of ANN, (**b**) for both indices RI and WAC together (inputs: T_d, v_d, T_r and L).

In the backward stepwise (BS) method used in this work for the discussed rehydration indices, namely RI and WAC and both RI and WAC together, four models were generated, considering only three out of the four variables (parameters), namely, T_d, v_d, T_r and L, as inputs. The omitted variable for which the generated models indicated the highest error (so the lowest value of R^2 and the highest value of RMSE) was regarded as the most important one. The BS results in which four models were generated by omitting one from the four considered variables are presented in Table 13. This table shows the values of R^2 and RMSE for each generated model.

Table 11. Weights and biases of ANNs for rehydration indices.

Rehydration Index	Weights and Biases between Layers of ANN								
	Input and Hidden					Hidden and Output			
	No.	Weights				Bias	Weights		Bias	
	i	$D_{1in\text{-}hid\_i}$	$D_{2in\text{-}hid\_i}$	$D_{3in\text{-}hid\_i}$	$D_{4in\text{-}hid\_i}$	$B_{in\text{-}hid\_i}$	$D_{hid\text{-}out\_1}$	$D_{hid\text{-}out\_2}$	$B_{hid\text{-}out\_1}$	$B_{hid\text{-}out\_2}$
RI	1	1.4223	3.4719	0.0789	0.0483	−3.8950	−1.4493		2.6578	
	2	−2.7266	3.8635	0.2521	0.4678	2.7240	1.2268			
	3	−0.6425	0.0878	−0.0362	5.7709	5.1401	−3.6946			
	4	−1.0771	−0.9887	−1.7848	−5.7598	2.1956	−1.4348			
WAC	1	3.5059	−4.0066	0.8629	−4.6100	2.0212	−0.0432		2.7519	
	2	0.45239	−3.9539	−1.7749	−2.6745	−1.1051	−0.8289			
	3	0.1079	−0.7704	−0.0898	6.0285	6.5638	−5.1909			
	4	0.6567	−5.3133	−0.4883	0.7898	4.8056	2.5714			
RI + WAC	1	9.8042	−16.1895	0.0718	1.7426	−15.6224	−0.9165	−0.8905	−5.5918	−5.9015
	2	−0.4290	1.8800	0.3195	−17.017	−18.9434	13.0804	14.3147		
	3	0.6545	−9.7334	−0.5522	−4.3675	5.7102	5.7079	6.1074		
	4	−13.3228	6.3649	−10.1912	9.2477	−8.3975	−0.3901	−0.3650		

Table 12. Results of statistical analyses on the modelling (using ANNs) of rehydration indices.

Rehydration Indices	Refer to	R^2	RMSE
RI	RI	0.9207	0.0584
WAC	WAC	0.9078	0.2285
RI + WAC	RI	0.9348	0.0529
	WAC	0.9327	0.0549
	RI + WAC	0.9347	0.0539

Table 13. Sensitivity analysis on the modelling of rehydration indices—BW method.

Rehydration Index	Omitted Parameter	R^2	RMSE
RI	T_d	0.3539 (2) *	0.2484 (2)
	v_d	0.3539 (2)	0.2844 (2)
	T_r	0.8783 (3)	0.0613 (3)
	L	0.2139 (1)	0.7067 (1)
WAC	T_d	0.4325 (2)	0.2127 (4)
	v_d	0.4325 (2)	0.4811 (3)
	T_r	0.7655 (3)	0.5518 (2)
	L	0.2295 (1)	0.7068 (1)
RI + WAC	T_d	0.5077 (2)	0.2013 (2)
	v_d	0.5077 (2)	0.201 (2)
	T_r	0.8800 (3)	0.0801 (3)
	L	0.1536 (1)	0.2510 (1)

* Parameter impact classification.

It can be concluded from the obtained results, that the L of red beets had the greatest influence on the considered indices both determined separately and together. As far as RI and both RI and WAC are concerned, T_d and v_d took second place, whereas the rehydration temperature occupied the third position. The same sequence was observed for rehydration index WAC, determined separately as far as the determination coefficient is concerned, whereas for RMSE, the rehydration temperature for this index took second place, v_d occupied the third position, and drying temperature took the fourth position.

It turned out from the conducted investigations that rehydration indices RI and WAC were influenced, but to a different degree, by both drying and rehydration conditions. As it was stated earlier, the rehydration kinetics, mass gain, volume increase, dry matter loss, and moisture content increase, depended also on T_d, v_d, L, and T_r. The reason for the

observed dependences is the fact that rehydration is a complicated process connected with the structural (physical and chemical) changes that occur in the vegetal cells and tissues of biological product during predrying treatments, drying and also rehydration [78,79].

4. Conclusions

The Page model and modified Page model can be accepted as the most suitable for the description of mass gain (adjusted R^2 = 0.9671–0.9964, RMSE = 0.0179–0.0528) and volume increase (adjusted R^2 = 0.9414–0.9947, RMSE = 0.0210–0.0877), whereas the Peleg model can be treated as the most appropriate for characterizing the dry matter loss (adjusted R^2 = 0.9368–0.9944, RMSE = 0.0135–0.0362), and the modified Page model can be accepted as the most appropriate for the moisture content increase (adjusted R^2 = 0.9625–0.9928, RMSE = 0.0267–0.0603) during the rehydration process for dried red beets. The constants of the investigated models depended (although to a different degree) on the parameters of drying and rehydration processes. It can be concluded from the results of statistical analyses on the modelling of mass, volume, dry matter, and moisture content changes during the rehydration of dried red beets (at model constants expressed as functions of drying and rehydration conditions) that the following models can be recommended as the most acceptable: (1) the modified Page model for mass gain (adjusted R^2 = 0.9628–0.9964, RMSE = 0.0236–0.0897) and for volume increase (adjusted R^2 = 0.9314–0.9945, RMSE = 0.0213–0.0972), (2) the Peleg model for dry matter loss (adjusted R^2 = 0.9348–0.9945, RMSE = 0.0161–0.0610), and (3) the Henderson–Pabis model for moisture content increase (adjusted R^2 = 0.9368–0.9920, RMSE = 0.0350–0.1062). The ANN (MLP 4-4-2) adopted to characterize both indices RI and WAC together can be accepted as the most appropriate for the prediction of these indices (R^2 = 0.9327–0.9348, RMSE = 0.0529–0.0549). A sensitivity analysis of artificial neural networks (using the backward stepwise method) indicated that the characteristics dimension of red beets had the greatest impact on RI and WAC.

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