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Mathematical Description of Changes of Dried Apple Characteristics during Their Rehydration

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Abstract: The mathematical description of changes of dried apples characteristics (mass gain, volume increase, dry matter loss, rehydration indices, and colour) during their rehydration was performed. The effect of conditions of both processes on model parameters were also considered. Apple slices (3 and 10 mm) and cubes (10 mm) were dried in natural convection (drying air velocity 0.01 m/s), forced convection (0.5 and 2 m/s), and fluidisation (6 m/s). Drying air temperatures (T_d) were equal to 50, 60, and 70 °C. The rehydration process was carried out in distilled water at the temperatures (T_r) of 20, 45, 70, and 95 °C. Mass gain, volume increase, and dry matter loss were modelled using the following empirical models: Peleg, Pilosof–Boquet–Batholomai, Singh and Kulshrestha, Lewis (Newton), Henderson–Pabis, Page, and modified Page. Colour changes were described through applying the first-order model. Artificial neural networks (feedforward multilayer perceptron) were applied to make the rehydration indices and colour variations (ΔE) dependent on characteristic dimension, T_d, drying air velocity, and T_r. The Page and the modified Page models can be considered to be the most appropriate in order to characterise the mass gain (RMSE = 0.0143–0.0619) and the volume increase (RMSE = 0.0142–0.1130), whereas the Peleg, Pilosof–Bouquet–Batholomai, and Singh and Kulshrestha models were found to be the most appropriate to characterise dry matter loss (RMSE = 0.0116–0.0454). The ANNs described rehydration indices and ΔE satisfactorily (RMSE = 0.0567–0.0802). Both considered process conditions influenced (although in different degree) the changes of the considered dried apple characteristics during their rehydration.

Keywords: rehydration; apple; quality; mathematical model; ANN

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1. Introduction

Apples, one of the oldest fruits known to human beings, are among the most popular fruits around the word [1]. Apples are cultivated all over the word, and the global production reaches about 87 million tons per year [2]. Poland belongs to the one of the major apple producers. The annual production of these fruits amounted in 2020 to around 3 million tons. Apples are very important in the human diet, and therefore they are eaten in all parts of the word [3]. These low caloric fruits have a high water content (80–85 w.b.) and consist of 12–14% carbohydrate and 2–3% fiber (including soluble fiber, namely, pectins). Apples are also high in vitamins (C and A) and minerals such as potassium, calcium, and magnesium [4]. These fruits are helpful in diabetes prophylaxis, maintaining the weight and reducing the asthma effect. Pectins decrease the level of cholesterol and eliminate toxic substances such as heavy metals from the organism. Carbohydrates cause slow and safe growth of glucose level in the blood and maintain it at a constant level for a longer period of time, influencing human health in a positive manner [5]. Apples are consumed fresh but are also added to many foods (e.g., desserts), beverages, and jam. The contemporary lifestyle, however, gives rise to a necessity for introducing innovative products to the market that are suitable for changing lifestyle and work pace. On the other hand, however, current consumers pay great attention to eating healthy foods. Dried fruits, among them, apples, can fulfil these requirements. Processed fruits are available on the market throughout the year. Dehydrated apples are often used in snack food, breakfast food, and as an ingredient of special diets. Many dried food products can be eaten after their rehydration, for example, in water, milk, yogurt, or fruit juices. Therefore, a better understanding of drying and rehydration processes can enable the improvement of the quality of both dehydrated and rehydrated products [1,6,7].

Drying is one of the oldest and most common methods to preserve agricultural products (vegetables, fruits, herbs, spices). By reducing moisture content, dehydration can prevent enzymatic reactions and microbiological activities. Therefore, drying is a preservation method that enables the decrease in product moisture content to a stable level. Dehydration of biological materials can be conducted using different methods such as, for example, sun-drying, convective drying, infrared drying, microwave drying, vacuum freezing, freeze-drying, and the combinations of abovementioned methods [8,9].

Several reviews about the drying of fruits and vegetables and about the food processing industry can be found in the literature [10–12]; nevertheless, questions connected with drying of biological materials are still widely investigated. Abbaspour-Gilandeh et al. [9] studied the influence of pretreatments on the course convective and infrared drying of terebinth and on energy consumption and quality of dried terebinth. Dadan and Nowacka [13] investigated the effect of ethanol and ultrasound application as pretreatment on the kinetics of carrot convective drying and properties of dried carrot tissue. Chupawa et al. [14] studied preparing instant red jasmine rice through applying fluidised bed drying assisted with swirling compressed air. Jeevarthinam et al. [15,16] investigated the effect of infrared-assisted hot air drying parameters on drying kinetics and quality of turmeric. Delfiya et al. [17] studied the drying kinetics and quality of food materials dried in infrared radiation drying. Pravitha et al. [18] and Pandiselvam et al. [19] investigated the effect of osmotic dehydration on dried food product quality. Srinivas et al. [20] studied the influence of the microwave-assisted fluidised bed drying parameters on nutmeg mace quality. Zhang et al. [21] investigated the impact of radio frequency treatment on the textural properties of food products.

Rehydration is a complicated process directed to restore the original properties of the raw product by immersing the dried food in liquid [22]. During the discussed process taking place, three processes occur, namely, liquid absorption by the dried material, product swelling, and leaching of the solubles such as vitamins or minerals from the material to the rehydrating liquid [23]. The course of the mass transfer depends on the rehydrating medium. It can be stated that during the process of rehydration occuring chiefly following crosscurrent mass fluxes, a water flux from the rehydrating medium to the rehydrated material and a soluble flux from the material to the rehydrating liquid. The kinetics of both processes depends on the immersion liquid [24]. Rehydration characteristics and the worsening of the sensory qualities depend on the structural changes after pre-drying treatments, drying, and rehydration. Hot drying air can cause, among other factors, the degradation of nutritional ingredients and flavour components and changes in dried food colour [9,25,26]. Processes which take place during moistening of dry product cause the changes in the composition and the structure of the product being rehydrated, which in a negative manner influence the reconstitution properties. Physical and chemical changes occurring during pre-drying treatments, drying, and rehydration show that rehydration cannot be considered to be the reversed process of drying. Therefore, rehydration can be treated as a quality criterion informing us of structural and chemical injuries caused by dehydration and the treatments before drying [27]. The knowledge of the rehydration characteristics of dried material is very important for the quality improvements of both dried and rehydrated products [28], and therefore the issues concerning rehydration are still widely investigated by many researchers. Górnicki [29] and Górnicki et al. [30] reviewed rehydration indices and mathematical models describing the rehydration process. Phukasmas and Songsermpong [31] studied the influence of various rice cooking methods on the quality of jasmine instant rice dehydrated using microwaves. Bochnak-Niedźwiecka and Świeca [32] investigated the quality of functional powdered beverages enriched by adding lyophilised fruits. Nisoa et al. [33] considered the possibility of applying microwave dehydration in the production of rehydrated food such as stink beans. The effect of pretreatments and method of drying on such quality attribute of dried material as rehydration rate has been studied lately, among others, by Fijałkowska et al. [34] and Boy et al. [2] for apples, Costa Santos et al. [35] and Dadan and Nowacka [13] for carrots, Rojas et al. [36] for pumpkins, Chupawa et al. [14] for red jasmine rice, and Abbaspour-Gilandeh et al. [9] for terebinth.

Colour characteristics are major quality parameters of processed and unprocessed foods. Colour is a decisive factor for the potential consumer that influence acceptance of the product. The discussed parameter also indicates chemical changes which have occurred in the food, for example, loss of the pigment nutrients such as carotenoids, flavonoids, or phenols [37,38]. Colour degradation is the effect of enzyme activity and nonenzymatic browning, including sugar caramelisation and Maillard reaction [39]. The colour of dried products was investigated among others for apple [6], carrot [40], and terebinth [9], whereas discussed quality attribute was studied, e.g., for apple [41], chestnuts [23], and red bell pepper [42].

Artificial neural networks (ANNs) are capable of modelling nonlinear and complex systems with a large amount of input and output data [43]. A neural network's ability to predict is dependent on its structure (number of layers, number of neurons in the hidden layer, type of activation function) [44]. The methods based on ANNs have been used to predict the moisture content of many dried agriculture products, i.e., apple [1] and shelled corn [45]. Pandiselvam et al. [46] used ANN for modelling microwave processing parameters for tender coconut water. Srikanth et al. [47] used ANN for modelling and optimisation of cocoa bean extractor parameters. Kothakota et al. [48] modelled and optimised process parameters for nutritional enhancement in enzymatic milled rice by ANN.

To predict the migration of water in foods, the theoretical and empirical models were 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, however, are based on the general theory of heat and mass transfer laws—they consider the fundamentals of the drying and rehydration processes, and their parameters have physical meaning. On the other hand, however, these models are more difficult in application compared to empirical models [49], and the constants of empirical models can inform us about the rate of the described process. Knowing the values of these constants (or the possibility of calculating from the appropriate formulas) makes it possible to easily obtain the information about mass transfer in materials. Additionally, in situations where the relationship between various variables describing the characteristics of rehydrated apple is complicated, the ANN can be a useful tool for solving these problems.

The aims of the present study were as follows:

- mathematical description of changes of dried apples characteristics (mass gain, volume increase, dry matter loss, rehydration indices, and colour) during their rehydration;
- application of the empirical models used in the literature, ANNs, and models not yet used for the description of the rehydration process;
- development of equations to calculate the constants of applied rehydration models;
- investigation of the effect of drying and rehydration conditions on changes of dried apple characteristics.

2. Materials and Methods

Apple var. Ligol were bought from Warsaw market, Poland. Ligol is a dessert variety. Its flesh is cream-coloured and very juicy and tasty [50]. In order to assure the homogenous fruits, maturity indicators such as apple appearance and size were taken into consideration [51]. Before the experiments, fruits were washed, hand peeled, cut into 3-milimetere and 10-milimetere thick slices and 10-milimetere thick cubes.

The apple characteristic dimension L was determined according to [52] as

- for slices, $L = s$;
- for cubes, $L^{-2} = 3\ s^{-2}$;

where s is the half of the slice thickness and cube thickness (mm).

The initial moisture content of the fresh apples was around 85% w.b. (5.7 d.b.).

Drying was conducted the same day the fresh apple samples were prepared. The following drying methods were applied: natural convection in chamber dryer (thin layer; drying air velocity v_d = 0.01 m/s; the laboratory dryer KCW-100 (PREMED, Marki, Poland)), forced convection in tunnel dryer (thin layer; v_d = 0.5 and 2 m/s; the laboratory dryer constructed in the Department of Fundamental Engineering and Energetics, Warsaw University of Life Sciences, Warsaw, Poland), and fluid bed drying in a laboratory-fluidised bed dryer (v_d = 6 m/s; the laboratory dryer constructed in the Department of Fundamental Engineering and Energetics, WULS, Warsaw, Poland). The drying methods used in this study are widely applied in drying, especially of agriculture products at industrial scales. The experiments were conducted at drying air temperatures T_d = 50, 60, and 70 °C (RH was in the range of 20–60%). The used range of T_d is typical for agriculture product drying [17]. The final moisture content of dried apples was about 9% w.b. (0.1 d.b.). The drying equipment used and the way of carrying out the experiments was described in the papers by Górnicki and Kaleta [53], Kaleta and Górnicki [54], and Kaleta et al. [55]. Dried material (the same drying conditions) obtained from three independent drying experiments was mixed and next stored in a sealed container (without exposure to sunlight) for seven days at the temperature 20 °C.

The rehydration process of dried apples was carried out in distilled water at the temperature T_r = 20, 45, 70, and 95 °C (applied T_r are widely used in the literature, the value of the T_r is dependent on the further use of rehydrated product). The temperature conditions were warranted with a water bath. The process lasted 2 h at medium temperature 95 °C, 4 h at 70 °C, 5 h at 45 °C, and 6 h at 20 °C. The mass of dried apple sample at the beginning of each experiment was approximately 10 g. The distilled water temperature was maintained constant, and water was not stirred during the experiment. Mass of dried sample to rehydration medium mass ratio was 1:20 (at the beginning of process). The sample mass m was measured applying the WPE 300 scales (RADWAG, Radom, Poland) with ±0.001 g accuracy. The sample dry matter $m_{d.m.}$ was determined in accordance with AOC standards [56]. The sample volume V was determined by applying the buoyancy method in petroleum benzine [57], and the relative error was lower than 5%. The experiments of mass, dry matter, and volume determination were conducted in three repetitions.

The scanner (CanoScan 5600F, Canon Inc., Tokyo, Japan, 4800 × 9600 dpi) was applied for determining the colour attributes for fresh, dried, and rehydrated apple sample. Obtained colour images (20 images for each apple batch) were loaded into the sRGB colour space. The mean brightness of pixels in each RGB channel of the image was used to express colour parameters. The ImageJ (ver.47i, Madison, WI, USA) software was used. A way of carrying out the colour measurements was described in the paper by Winiczenko et al. [58].

Although several mechanisms have been proposed in the literature to describe rehydration process on the basis of different mass transports, it is not clear which is the predominant mechanism [59]. Many theoretical and empirical approaches have been employed, and in some cases, empirical models were preferred. Among the various proposed models, empirical ones are the most widely used because of their mathematical simplicity and utility [23]. The discussed models are not only very useful but their interpretation also provides valuable information about the course of the rehydration because model constants have physical meaning.

Models employed to characterise the rehydration kinetics of dried apple are shown in Table 1.

Nomenclature for the equations given in Table 1 is as follows: t is the time (h); $A_1 \div A_6$; and a, k, and n are the constants (and they have a physical meaning, informing them about the rate of the described process).

Table 1. Empirical models applied to rehydration kinetics of dried apples.

Model No.	Model Equation	Model Name	References
(1)	$X = 1 \pm \frac{t}{A_1 + A_2 t}$ *	Peleg	[60]
(2)	$X = 1 + \frac{A_3 t}{A_4 + t}$	Pilosof–Boquet–Batholomai	[61]
(3)	$X = 1 + \frac{A_5 A_6 t}{A_6 t + 1}$	Sing and Kulshrestha	[62]
(4)	$Y = \exp(-kt)$	Lewis (Newton)	[63]
(5)	$Y = a\exp(-kt)$	Henderson–Pabis	[64]
(6)	$Y = \exp(-kt^n)$	Page	[65]
(7)	$Y = \exp\left[-(kt)^n\right]$	Modified Page	[66]

* Sing minus for the dry matter of solid loss.

Variable X denotes the ratio: mass of rehydrated sample to the mass of dried material used for rehydration (m/m_0), volume of the rehydrated sample to the volume of the dried material used for rehydration (V/V_0), and dry matter of the rehydrated sample to the dry matter of dried material used for rehydration ($m_{d.m.}/m_{d.m.0}$).

The variable Y (the values of mass gain, dry matter loss, and the volume increase were normalised to the range 0–1) is determined according to the following equations:

- for the mass gain and the volume increase

$$Y = \frac{X - 1}{X_e - 1}, \tag{8}$$

- for the dry matter loss.

$$Y = X, \tag{9}$$

where X_e denotes the equilibrium value. It can be determined from the Peleg model, Pilosof–Boquet–Batholomai model, and the Singh and Kulshrestha model, making the assumption that the process of rehydration lasted long enough and therefore $t \to \infty$. The discussed value can be determined according to the following equations:

- for the Peleg model

$$X_e = 1 \pm \frac{1}{A_2}, \tag{10}$$

- for the Pilosof–Boquet–Batholomai model

$$X_e = 1 + A_3, \tag{11}$$

- for the Singh and Kulshrestha model

$$X_e = 1 + A_5. \tag{12}$$

It turned out from the calculations that the error of the difference between the values of X_e determined from the abovementioned models was not greater than 0.2%; therefore, to count the variable Y, the equilibrium value determined from the Peleg model was taken.

Empirical models (1)–(3) (Table 1) were developed to describe the rehydration process. As was mentioned above, they were easy to apply, and, very importantly, their constants have physical meaning. Constants A_1, A_4, and A_6 provide the information about the rate of water absorption during the process, especially in its early stage, whereas constants A_2, A_3, and A_5 allow for the prediction of water absorption kinetics for a relatively long period of absorption and inform us about the maximum capacity of water absorption. The Peleg, Pilosof–Boquet–Batholomai, and Singh and Kulshrestha models have been widely used for describing the relational process of biological materials. The Peleg model has been applied to describe, among others, the rehydration process of the following dried materials: kiwi [67], paraboiled rice [68], and squid fillets [69]. The Pilosof–Boquet–Batholomai model has been used to predict the rehydration of water uptake to food powders [61], water absorption of wheat starch, whey protein concentrate, and whey protein isolate [49]. The Singh and Kulshrestha model, in turn, has been applied to predict the rehydration kinetics of soybean and pigeonpea grains [62], wheat starch, whey protein concentrate, and whey protein isolate [49].

Empirical models (4)–(7) (Table 1) were developed to describe the drying process; however, two of them, namely, the Lewis (Newton) model and the Page model, have been adopted to predict the rehydration process. The Lewis model (a first-order kinetics model) gave good results in the rehydration prediction of dried products such as mangoes [70], paraboiled rice [68], pumpkin [71], rice porridge [72], and soybean curd [73]. The Page model has been applied to predict the rewetting of dried pumpkin [71] and rough rice [74]. The Henderson and Pabis model and the modified Page model have not yet been used for description of dried product rehydration. Constant k in models (4)–(7) has physical meaning and informs us about the rate of the dried material rehydration.

Rehydration curves were fitted to seven considered models (Table 1). The Matlab (Curve Fitting Toolbox 2018a, MathWorks, Inc., Natick, MA, USA) software (with the Levenberg–Marquardt algorithm) was used. The following statistical test methods were applied to statistically evaluate the suitability of the discussed models for predicting the rehydration kinetics of dried apples: sum squared error (SSE) coefficient of determination R^2, adjusted R^2, and root mean square error RMSE. These statistical criteria are widely used in the literature.

In this work, the effect of characteristic dimension L, drying air temperature T_d, drying air velocity v_d, and rehydration temperature T_r on the model constants were also studied. The constants of the models (1)–(7) (Table 1) involving the mentioned drying and rehydration conditions were determined by investigating the following type of equation:

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

where $a_0 \div a_{14}$ are constants. The statistical analysis ANOVA was used.

The following quality indices were applied to describe rehydration of dried apples.

- Index RI_1 (in kg_{reh}/kg_{dry}):

$$RI_1 = \frac{\text{mass of material after rehydration}}{\text{mass of dired material}}, \tag{14}$$

- Index RI_2 (in kg_{reht}/kg_{raw}):

$$RI_2 = \frac{\text{mass of material after rehydration}}{\text{mass of raw material}}, \tag{15}$$

- water absorption capacity WAC:

$$\text{WAC} = \frac{m_r(100 - s_r) - m_d(100 - s_d)}{m_0(100 - s_0) - m_d(100 - s_d)}, \tag{16}$$

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

The WAC index has been widely applied to express the rehydration characteristics [22,75].

The rehydration indices RI_1, RI_2, and WAC were predicted with feedforward multilayer perceptron (MLP) artificial neural networks (ANNs) in Matlab (Neural Network Toolbox 2018a, MathWorks, Inc.). The inputs L, T_d, v_d, and T_r and outputs RI_1, RI_2, and WAC were normalised to range 0–1 using the *minmax* method. The cases were randomly divided into training set—70%, validation set—15%, and testing set—15%. The following statistical test methods were used to evaluate statistically the suitability of applied model: SSE, R^2, adjusted R^2, and RMSE.

In order to determine the rate of dried apple colour changes during their rehydration, kinetics of the following colour parameters were investigated: lightness L^*, yellowness b^*, hue angle h^*, and chroma C^*. The first-order model was applied to characterise the kinetics of the mentioned colour parameters:

$$Z = \exp(-k_c t), \tag{17}$$

where Z is the normalised to range 0–1 (*minmax* method) colour parameters: L^*, b^*, h^*, and C^*; k_c is the rate of colour degradation; and t is the time (min).

The course of the considered colour parameter changes was fitted to the first-order model. The following statistical test methods were used to statistically evaluate the suitability of the applied model: SSE, R^2, adjusted R^2, and RMSE.

The following characteristic dimension L, drying air temperature T_d, drying air velocity v_d, and rehydration temperature T_r on the model constant k_c were also studied. Equation (13) was used for this purpose.

The colour variations ΔE (total colour difference) between fresh (standard) and rehydrated (tested) material were determined according to the following equation [76]:

$$\Delta E = \left\{ \left(\frac{\Delta L^*}{K_L S_L} \right)^2 + \left(\frac{\Delta C^*}{K_C S_C} \right)^2 + \left(\frac{\Delta H^*}{K_H S_H} \right)^2 + \right\}^{0.5}, \tag{18}$$

where S_L, $S_{C,}$ and S_H are the weighting functions adjusted the internal non-uniform structure of the CIE$L^*a^*b^*$ calculated using Formulas (19)–(21), respectively:

$$S_L = 1, \tag{19}$$

$$S_C = 1 + 0.045C^*, \tag{20}$$

$$S_H = 1 + 0.015C^*, \tag{21}$$

where K_L, K_C, and K_H denote parametric factors describing the effect from reference conditions (they are all taken as 1) and

$$\Delta L^* = L_T{}^* - L_s{}^*, \tag{22}$$

$$\Delta C^* = C_T{}^* - C_s{}^*, \tag{23}$$

$$\Delta H^* = 2\sqrt{C_T{}^* C_s{}^*} \sin\left(\frac{\Delta h^*}{2} \right), \tag{24}$$

where subscript T and S refer to tested and standard samples, respectively.

The colour variations ΔE was modelled with MLP artificial neural network in Matlab (Neural Network Toolbox 2018a, MathWorks, Inc.). The inputs L, T_d, v_d, T_r, and t (time of rehydration process) were normalised to range 0–1 using the *minmax* method. The cases were randomly divided into training set—70%, validation set—15%, and testing set—15%. The following statistical test methods were used to statistically evaluate the suitability of the applied model: SSE, R^2, adjusted R^2, and RMSE.

3. Results and Discussion

The summary results of statistical analyses on the modelling of mass, volume, and dry matter changes during the rehydration of dried apples are given in Table 2. As can be concluded from the statistical analysis results, all considered models may be assumed to characterise mass gain during the rehydration of dried apples. The R^2 values varied between 0.9541 and 0.9981, and only the Lewis (Newton) and Henderson and Pabis models were within 0.8840 to 0.9549. On the other hand, however, the SSE values for two mentioned models fell within the range of 0.0660 to 0.2210, and the RMSE ones varied between 0.0580 and 0.1064, whereas for the Peleg, Pilosof–Bouquet–Batholomai, and Singh and Kulshrestha models, the discussed values were between 0.0488 and 0.6592 for SSE and 0.0570 and 0.1910 for RMSE. Taking into account, however, the values of all considered statistical test methods (SSE, R^2, adjusted R^2, and RMSE), it can be stated that the Page and the modified Page models can be considered to be the most appropriate. Their sum squared error varied between 0.0027 and 0.0843, the coefficient of determination ranged from 0.9541 to 0.9981, the adjusted coefficient of determination changed from 0.9520 to 0.9980, and the root mean square error fell within the range of 0.0143 to 0.0619.

Table 2. Summary results of statistical analyses on the modelling of mass, volume, and dry matter changes during the rehydration of dried apples.

Model No.	Model Name	Variable	SSE	R^2	Adjusted R^2	RMSE
(1)	Peleg	mass gain	0.0488–0.6590	0.9597–0.9966	0.9578–0.9964	0.0570–0.1910
		volume increase	0.0203–0.4924	0.8622–0.9950	0.8631–0.9946	0.0430–0.1496
		dry matter loss	0.0018–0.0385	0.9329–0.9976	0.9299–0.9974	0.0116–0.0454
(2)	Pilosof–Boquet–Batholomai	mass gain	0.0488–0.6590	0.9597–0.9966	0.9578–0.9963	0.0570–0.1910
		volume increase	0.0203–0.4924	0.8622–0.9950	0.8531–0.9946	0.0430–0.1496
		dry matter loss	0.0018–0.0385	0.9329–0.9976	0.9299–0.9974	0.0116–0.0454
(3)	Singh and Kulshrestha	mass gain	0.0488–0.6592	0.9597–0.9966	0.9578–0.9963	0.0570–0.1910
		volume increase	0.0203–0.5129	0.8452–0.9950	0.8349–0.9946	0.0430–0.1527
		dry matter loss	0.0018–0.0385	0.9329–0.9973	0.9299–0.9966	0.0116–0.0452
(4)	Lewis (Newton)	mass gain	0.0763–0.2210	0.8840–0.9481	0.8840–0.9481	0.0738–0.1064
		volume increase	0.0671–0.3131	0.8071–0.9492	0.8071–0.9492	0.0731–0.1326
		dry matter loss	0.0501–0.2417	0.8398–0.9672	0.8398–0.9672	0.0646–0.1183
(5)	Henderson–Pabis	mass gain	0.0660–0.1952	0.8997–0.9549	0.8930–0.9519	0.0580–0.1033
		volume increase	0.0610–0.2440	0.8327–0.9538	0.8215–0.9513	0.0636–0.1276
		dry matter loss	0.0476–0.2741	0.8590–0.9688	0.8523–0.9660	0.0652–0.1142
(6)	Page	mass gain	0.0037–0.0582	0.9541–0.9981	0.9520–0.9970	0.0143–0.0619
		volume increase	0.0022–0.2092	0.8686–0.9983	0.8598–0.9982	0.0142–0.1130
		dry matter loss	0.0050–0.2267	0.8834–0.9969	0.8778–0.9966	0.0195–0.1039
(7)	Modified Page	mass gain	0.0027–0.0843	0.9541–0.9981	0.9520–0.9980	0.0143–0.0619
		volume increase	0.0022–0.2092	0.8686–0.9983	0.8598–0.9982	0.0142–0.1130
		dry matter loss	0.0050–0.2267	0.8834–0.9969	0.8778–0.9966	0.0195–0.1039

As for as the changes of dried apple volume during the rehydration, it was found that all models except the Lewis (Newton) and Henderson and Pabis models described the volume increase quite satisfactorily. The R^2 values were between 0.8452 and 0.9983, and only two mentioned models varied between 0.8071 and 0.9538. Taking into account all considered statistical test methods, it can be assumed that the Page model and the modified Page model characterised the volume increase during dried apple rehydration in the most acceptable way. The values of the considered statistical test methods for both models were as follows: SSE = 0.0022–0.2092, R^2 = 0.8686–0.9983, adjusted R^2 = 0.8598–0.9982, RMSE = 0.0142–0.1130.

It turned out from the statistical analysis results that all models except the Lewis (Newton) model fitted well to the experimental data of dry matter loss during the rehydration of dried apples. The values of determination coefficient fell within the range of 0.8590 to 0.9976 for models (1)–(3) and (5)–(7), whereas the Lewis (Newton) model varied between 0.8398 and 0.9672. Taking into consideration, however, all applied statistical test methods, the Peleg, Pilosof–Boquet–Batholomai, and Singh and Kulshrestha models can be selected as the most suitable models to represent the dry matter loss during the rehydration of dried apples. The sum squared error for three mentioned models ranged from 0.0018 to 0.0385, the coefficient of determination varied between 0.9329 and 0.9976, the adjusted coefficient of determination changed from 0.92299 to 0.9974, and the root mean square error fell within the range of 0.016 to 0.0454.

The results of investigation of the effects of characteristic dimension L, drying air temperature T_d, drying air velocity v_d, and rehydration temperature T_r on the model constants are shown in Table 3 for the models applied to mass gain during rehydration of dried apples, in Table 4 for the models applied to volume increase, and in Table 5 for the models applied to dry matter loss.

Table 3. Parameter equations for the models applied to mass gain during rehydration of dried apples.

Model No.	Model Name	Parameter Equations
(1)	Peleg	$A_1 = 0.087419 - 2.2 \times 10^{-5} \cdot T_d^2 + 0.02319 \cdot L^2 - 1.8 \cdot 10^{-5} \cdot T_r^2 + 0.00422 \cdot T_d \cdot v_d - 0.08602 \cdot v_d \cdot L$ $A_2 = 0.329564 + 2.97 \times 10^{-5} \cdot T_d^2 - 0.00178 \cdot T_d \cdot v_d + 0.00042 \cdot T_d \cdot L + 0.0339644 \cdot v_d \cdot L - 0.00125 \cdot L \cdot T_r$
(2)	Pilosof–Boquet–Batholomai	$A_3 = 3.045997 - 0.00028 \cdot T_r^2 + 0.014144 \cdot T_d \cdot v_d - 0.00385 \cdot T_d \cdot L - 0.31729 \cdot v_d \cdot L + 0.011896 \cdot L \cdot T_r$ $A_4 = 0.280897 + 0.04096 \cdot L^2 - 5.5 \times 10^{-5} \cdot T_r^2$
(3)	Singh and Kulshrestha	$A_5 = 2.252442 + 0.021388 \cdot T_d - 0.00031 \cdot T_r^2 - 0.00693 \cdot T_d \cdot L - 0.0265 \cdot v_d \cdot L + 0.013017 \cdot L \cdot T_r$ $A_6 = 4.083154 + 0.001954 \cdot T_r^2 - 0.04949 \cdot L \cdot T_r$
(4)	Lewis (Newton)	$k = 2.327949 + 0.001058 \cdot T_r^2 - 0.02735 \cdot L \cdot T_r$
(5)	Henderson–Pabis	$k = 1.940489 + 0.000939 \cdot T_r^2 - 0.02355 \cdot L \cdot T_r$ $a = 0.895178 + 7.94 \times 10^{-6} \cdot T_d \cdot T_r$
(6)	Page	$k = 0.72067 + 0.00015 \cdot T_r^2$ $n = 0.612353 - 9.7 \times 10^{-6} \cdot T_r^2$
(7)	Modified Page	$k = 2.20413 + 0.001114 \cdot T_r^2 - 0.02795 \cdot L \cdot T_r$ $n = 0.513102 + 0.000599 \cdot T_d \cdot L - 1.5 \cdot 10^{-5} \cdot T_d \cdot T_r$

Table 4. Parameter equations for the models applied to volume increase during rehydration of dried apples.

Model No.	Model Name	Parameter Equations
(1)	Peleg	$A_1 = 0.432052 + 0.0144 \cdot L^2 - 5.7 \times 10^{-5} \cdot T_r^2$ $A_2 = 0.064866 + 0.003357 \cdot v_d^2 + 0.042058 \cdot L^2 - 3.6 \times 10^{-5} \cdot T_r^2$
(2)	Pilosof–Boquet–Batholomai	$A_3 = 1.797968 - 0.00243 \cdot L \cdot T_r$ $A_4 = 0.33569 + 0.043488 \cdot L^2 - 6.2 \times 10^{-5} \cdot T_r^2$
(3)	Singh and Kulshrestha	$A_5 = 1.351868 - 0.00028 \cdot T_r^2 - 0.00101 \cdot T_d \cdot v_d + 0.000959 \cdot T_d \cdot T_r - 0.01163 \cdot L \cdot T_r$ $A_6 = 3.563119 + 0.001701 \cdot T_r^2 + 0.058523 \cdot T_d \cdot v_d - 0.00208 \cdot T_d \cdot T_r - 1.22396 \cdot v_d \cdot L$
(4)	Lewis (Newton)	$k = 1.968387 + 0.000829 \cdot T_r^2 - 0.02088 \cdot L \cdot T_r$
(5)	Henderson–Pabis	$k = 1.622107 + 0.000699 \cdot T_r^2 - 0.01724 \cdot L \cdot T_r$ $a = 0.914742$
(6)	Page	$k = 1.367971 + 0.0004 \cdot T_r^2 - 0.01023 \cdot L \cdot T_r$ $n = 0.623547 - 7.1 \times 10^{-6} \cdot T_r^2$
(7)	Modified Page	$k = 1.797016 + 0.000814 \cdot T_r^2 - 0.01995 \cdot L \cdot T_r$ $n = 0.623556 - 7.1 \times 10^{-6} \cdot T_r^2$

It is shown in Table 3 that parameters A_1, A_2, A_3, and A_5 for models such as Peleg, Pilosof–Bouquet–Batholomai, and Singh and Kulshrestha applied to describe the grain depended in a statistically significant manner on L, T_d, v_d, and T_r, whereas parameters A_4 and A_6 depended in a statistically significant way on characteristic dimension and rehydration temperature. As far as models 4–7 were concerned, the rehydration rate constant k depended statistically significantly on characteristic dimension and rehydration temperature for the Lewis (Newton), Henderson and Pabis, and modified Page models, whereas for the Page model, it depends only on T_r. Parameter a for the Henderson and Pabis model depends in a statistically significant manner on T_d and T_r; parameter n for the Page model depends on T_r; and parameter n for the modified Page model depends on L, T_d, and T_r. It turned out from the discussion that the dependence of the parameters of models 4–7 on drying air velocity was statistically insignificant. Taking into account the results presented in Tables 2 and 3, it can be stated that in the process of the prediction of the course of mass gain during the dried apple rehydration, L, T_d, v_d, and T_r should be taken into consideration, and the Peleg, Pilosof–Bouquet–Batholomai, or Singh and Kulshrestha models are the better choice. If, however, air drying velocity is not so very important for prediction, the best fit is the modified Page model.

Table 5. Parameter equations for the models applied to dry matter loss during rehydration of dried apples.

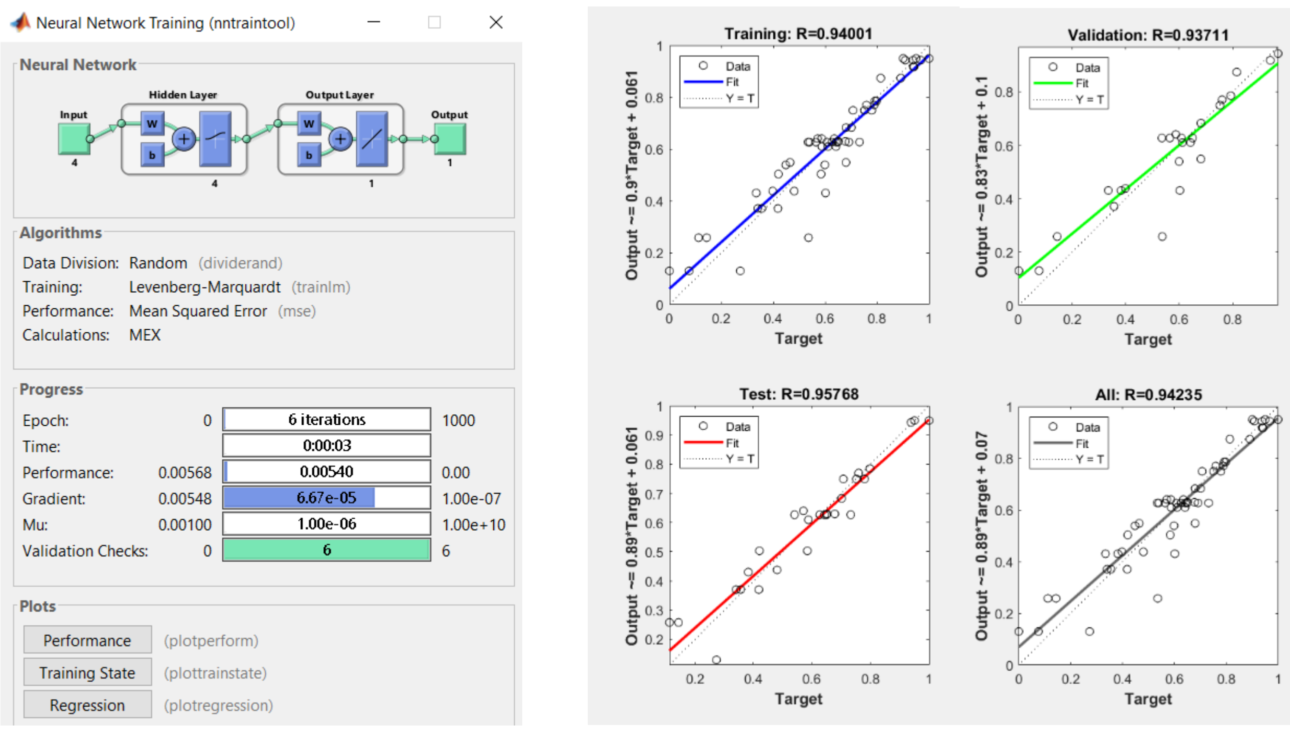
Model No.	Model Name	Parameter Equations
(1)	Peleg	$A_1 = 1.199471 + 0.03494 \cdot L^2 - 0.01674 \cdot T_d \cdot v_d + 0.000595 \cdot T_d \cdot T_r + 0.345962 \cdot v_d \cdot L - 0.0122 \cdot L \cdot T_r$ $A_2 = -0.09904 + 0.105514 \cdot L^2 + 0.018807 \cdot T_d \cdot v_d - 8.7 \times 10^{-5} \cdot T_d \cdot T_r - 0.38681 \cdot v_d \cdot L$
(2)	Pilosof–Boquet–Batholomai	$A_3 = 0.65515 - 0.00546 \cdot L^2 - 2.9 \cdot 10^{-5} \cdot {T_r}^2 + 0.003547 \cdot T_d \cdot v_d - 0.07355 \cdot v_d \cdot L + 0.00107 \cdot L \cdot T_r$ $A_4 = -0.02683 + 0.063203 \cdot L^2 + 0.018608 \cdot T_d \cdot v_d - 5.4 \times 10^{-5} \cdot T_d \cdot T_r - 0.38314 \cdot v_d \cdot L$
(3)	Singh and Kulshrestha	$A_5 = 0.658516 + 0.003843 \cdot T_d \cdot v_d - 0.07913 \cdot v_d \cdot L$ $A_6 = 3.234311 - 0.00966 \cdot T_d \cdot L + 0.000608 \cdot T_d \cdot T_r$
(4)	Lewis (Newton)	$k = 2.388268 - 0.06332 \cdot L^2$
(5)	Henderson–Pabis	$k = 1.048803 + 0.000156 \cdot {T_r}^2$ $a = 0.825358 - 4.6 \cdot 10^{-5} \cdot {T_r}^2\ 8.45 \times 10^{-5} \cdot T_d \cdot T_r$
(6)	Page	$k = 1.353281 - 0.02825 \cdot L^2 + 6.64 \times 10^{-5} \cdot {T_r}^2$ $n = 0.510797 + 0.005854 \cdot L^2$
(7)	Modified Page	$k = 1.098296 + 0.00019 \cdot {T_r}^2$ $n = 0.510797 + 0.005854 \cdot L^2$

According to Table 4, only parameters A_5 and A_6 for the Singh and Kulshrestha model applied to volume increase depended in a statistically significant manner on all considered drying and rehydration conditions, namely, characteristic dimension, drying air temperature, drying air velocity, and rehydration temperature. As far as the other models are concerned, the following parameters depend statistically significantly on L and T_r: A_1 for the Peleg model; A_3 and A_4 for the Pilosof–Boquet–Batholomai model; and k for the Lewis (Newton), Henderson and Pabis, Page, and modified Page models. It turned out from the investigation that parameter A_2 for the Peleg model depended in a statistically significant manner on L, v_d, and T_r, whereas parameter k (Page and modified Page models) depended only on T_r, and the dependence of parameter a for the Handerson and Pabis model on the all considered drying and rehydration conditions was statistically insignificant. Taking into account the results shown in Tables 2 and 4, it can be concluded that the application of the Singh and Kulshrestha model for the prediction of the volume increase during rehydration of dried apples enabled the taking into consideration of the influence of L, T_d, v_d, and T_r. If, however, drying conditions are not so very important for the process prediction, the Page and modified Page models seem to be the most appropriate.

It can be noticed (Table 5) that parameters A_1 and A_2 for the Peleg model and parameters A_3 and A_4 for the Pilosof–Boquet–Batholomai model used to characterise the dry matter loss during rehydration of dried apples depended in a statistically significant manner on all considered drying and rehydration conditions (L, T_d, v_d, T_r). Parameter A_5 dependence (for the Singh and Kulshrestha model) on rehydration temperature was statistically insignificant, whereas for A_6, the influence of drying air velocity was statistically insignificant. The situation for the models 4–7 appeared as follows. Parameter k for the Lewis (Newton) model, n for the Page model, and n for the modified Page model depended in a statistically significant manner only on characteristic dimension, whereas parameter k for the Henderson and Pabis model and k for the modified Page model depended in a statistically significant way on rehydration temperature. The influence of L and v_d on parameter a for the Henderson and Pabis model and T_d and v_d on parameter k for the Page model was statistically insignificant. Taking into consideration the results presented in Tables 2 and 5, it can be stated that the Peleg model and the Pilosof–Bouquet–Batholomai model enable the prediction of the dry matter loss kinetics during rehydration of dried apples, considering all drying and rehydration conditions, namely, characteristic dimension, drying air temperature, drying air velocity, and rehydration temperature.

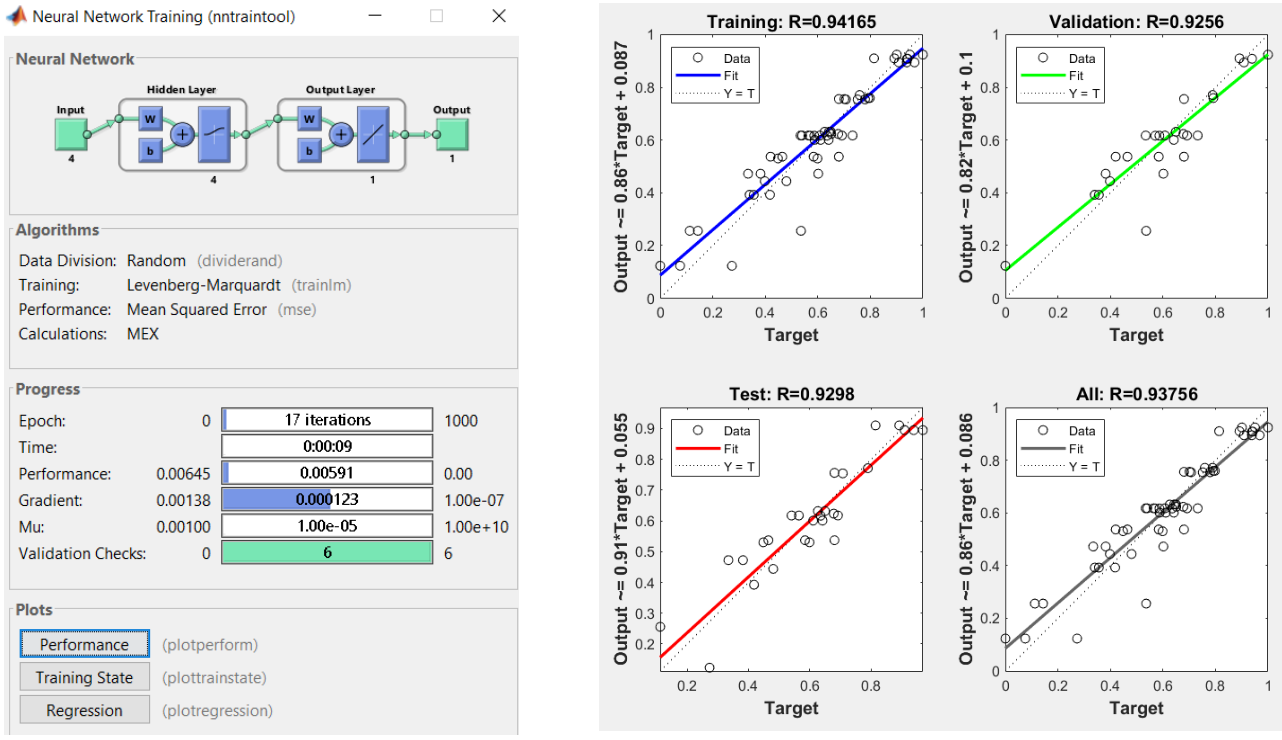
The obtained results of modelling using Peleg, Pilosof–Bouquet–Batholomai, Singh and Kulshrestha, Lewis (Newton), and Page models provides similar results to those reported in the literature [49,61,62,67–69,71–73], whereas the Henderson and Pabis model and modified Page model were used for the first time for the description of dried product rehydration. Although models 1–7 are not theoretical (they are empirical ones), the constants of these models have physical meaning and inform us about the rate of the dried material rehydration. The equations of the model constants obtained in the work allow, on the one hand, for the calculation of their values, and, on the other hand, their mathematical forms (performed statistical analysis) indicate the factors (parameters of drying and rehydration processes) influencing the apple rehydration process kinetics. The obtained results indicate that both drying and rehydration conditions influence (although to different degree) the constants of the rehydration models, and therefore mass, dry matter, and volume kinetics during rehydration. The kinetics of rehydration indicate the structural changes (and the changes in the composition) of rehydrated material as a result of pretreatment, drying, and rehydration. The literature data, e.g., [72,73], confirm the obtained results.

Different ANN structures were tested. The rehydration indices RI_1, RI_2, and WAC were predicted with ANNs. MLP 4-4-1 was used for RI_1 (Figure 1a), MLP 4-4-1 for RI_2 (Figure 2a), and MLP 4-3-1 for WAC (Figure 3a), with *logsig* transfer function in the hidden layer and *purelin* transfer function in the output layer. The *trainlm* training function (L-M) and *learngdm* (gradient descent with momentum weight and bias learning) adaptation functions were used. The highest values of R were obtained for ANN describing RI_1 (0.9371 for validation set), whereas for RI_2, R = 0.9256, and for WAC, R = 0.9203. Weights and biases between input and hidden layer and between hidden and output layers for rehydration indices RI_1, RI_2, and WAC are provided in Table 6.



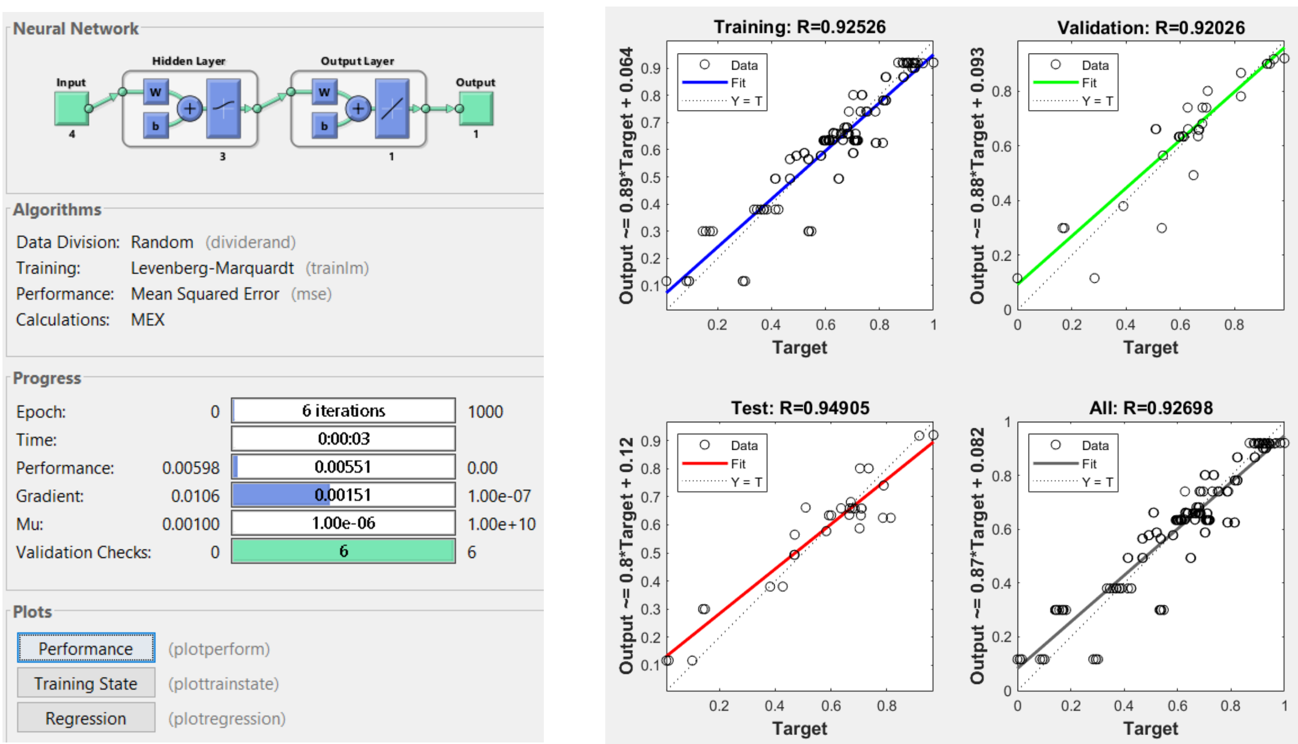
(**a**) (**b**)

Figure 1. The best ANN structure and window of ANN training (**a**); the ANN goodness of fit and correlation coefficients R between ANN and output (**b**) for index RI_1.



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

Figure 2. The best ANN structure (**a**) and the ANN goodness of fit and correlation coefficients R between ANN and output (**b**) for index RI_2.



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

Figure 3. The best ANN structure (**a**) and the ANN goodness of fit and correlation coefficients R between ANN and output (**b**) for index WAC.

Table 6. Weights and biases between input and hidden layer and between hidden and output layers for rehydration indices.

Rehydration Index	Weights and Biases between Input and Hidden Layer						Weights and Biases between Hidden and Output Layer	
	No.	**Weights**				**Bias**	**Weights**	**Bias**
	i	D_{1i}	D_{2i}	D_{3i}	D_{4i}	D_i	W_i	B_i
RI_1	1	0.76302	−4.30465	6.1141	4.1011	3.2308	3.8703	−1.0468
	2	−0.18017	5.2373	−2.251	−9.0609	−0.41154	0.46843	
	3	−5.4656	2.1371	−5.5557	4.6212	−1.931	4.4227	
	4	−8.7999	2.4317	−0.35888	3.979	0.66115	−6.7914	
RI_2	1	−1.8885	2.0685	1.1286	−0.37259	−2.3498	3.0742	0.79132
	2	0.50806	0.55895	−7.7709	−0.84271	0.62434	−2.1788	
	3	−3.4158	−0.11008	−10.5825	−1.202	0.85564	8.3004	
	4	0.32057	−4.9892	2.4163	−5.1056	1.52	3.3142	
WAC	1	−0.32603	−0.53705	−0.88337	2.8526	−2.0969	−1.0055	0.42304
	2	9.2834	−46.5133	−60.2563	122.4035	0.81527	7.7133	
	3	−22.1376	−52.8683	0.59559	19.7618	0.54159	−62.5777	

Table 7 shows the results of statistical analyses on the modelling of rehydration indices considered. The values of correlation coefficient R were high enough. The lowest R value (for all data) was received for the networks describing index WAC (0.9270), whereas the highest value was obtained for index RI_1 (0.9423). The gained values of RMSE were within the range of 0.0756 to 0.0802, and the lowest value demonstrated the neural networks describing rehydration index RI_1, while the network-characterised index WAC showed the highest value. As far as χ^2 is concerned, its values were as follows: 0.0065 for the neural networks describing index RI_1 and 0.070 for the network-characterised indices RI_2 and WAC. The obtained results show that all of the ANNs applied in this work predicted the behaviour of the considered rehydration indices satisfactorily.

Table 7. Results of statistical analyses on the modelling of rehydration indices.

Rehydration Index	R	RMSE	χ^2
RI_1	0.9424	0.0756	0.0065
RI_2	0.9376	0.0787	0.0070
WAC	0.9270	0.0802	0.0070

In the backward stepwise method applied in the present research, for each considered index, namely, RI_1, RI_2, and WAC, four models were generated, taking only three of the variables (parameters) as inputs. The variable not taken into account for which the resulting models gave the highest value of error was considered to be the most important one. Table 8 shows the backward stepwise results in which four models were generated, applying three of the discussed variables. The values of R, RMSE, and χ^2 of each generated model are shown in Table 8.

As can be seen from the obtained results, the characteristic dimension L of apples had the greatest impact on the two of considered rehydration indices, namely, RI_2 and WAC. As far as RI_1 is concerned, characteristic dimension took the first place for error of R, whereas for RMSE and χ^2, it occupied the second position. The air drying velocity had the least influence on all of the rehydration indices. The rehydration temperature influences considered indices to a lesser extent than the drying temperature (with the exception of R error for index RI_2).

The obtained results indicate that both drying and rehydration conditions influenced (although in different degree) the rehydration indices. The rehydration indices, the same as rehydration kinetics, indicated the structural changes that had arisen as a result of pretreatment, drying, and rehydration. The value of the rehydration indices being discussed is predominantly influenced by the mass of the rehydrated apple. This mass depends on the one hand on the amount of water absorbed, and on the other hand, on the amount of dry matter lost. Both of the masses depend on the degradation magnitude of changes during drying but also on the rehydration conditions. Increasing the T_r causes deterioration in the texture, which is connected by the damage caused during drying and promotes a significant loss in mechanical resistance and then causes the alterations of the mass transfer ability of the system [22].

Table 8. Sensitivity analysis for the rehydration indices—stepwise method.

Rehydration Index	Omitted Parameter	R	RMSE	χ^2
RI_1	T_d	0.76 (2) *	0.34 (1)	0.130 (1)
	v_d	0.84 (4)	0.14 (4)	0.021 (4)
	T_r	0.78 (3)	0.15 (3)	0.026 (3)
	L	0.21 (1)	0.29 (2)	0.096 (2)
RI_2	T_d	0.79 (3)	0.18 (2)	0.035 (2)
	v_d	0.84 (4)	0.13 (4)	0.020 (4)
	T_r	0.78 (2)	0.15 (3)	0.026 (3)
	L	0.45 (1)	0.23 (1)	0.062 (1)
WAC	T_d	0.76 (2)	0.14 (2)	0.022 (2)
	v_d	0.85 (4)	0.12 (4)	0.016 (4)
	T_r	0.82 (3)	0.14 (3)	0.021 (3)
	L	0.30 (1)	0.21 (1)	0.048 (1)

* Parameter impact classification.

Figure 4 presents the example images of the following samples: fresh, dried in force convection, and rehydrated in distilled water at 45 °C for 5 h. The summary results of statistical analyses on the modelling of lightness L^*, yellowness b^*, hue angle h^*, and chroma C^* changed during the rehydration of dried apples are shown in Table 9. As can be seen, the first-order model approximated the colour changes not quite satisfactorily. The inferior limit of determination coefficient R^2 was especially very low, namely, 0.2601 for h^*, 0.3516 for b^*, and 0.3611 for C^*. The discussed model can be therefore taken only for rough estimation of lightness, yellowness, hue angle, and chroma changes during rehydration.

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

Figure 4. The images of sample: fresh (**a**), dried in forced convection at 60 °C with 2 m/s (**b**), and rehydrated in distilled water at 45 °C for 5 h (**c**).

Table 9. Summary results of statistical analyses on the modelling of lightness L^*, yellowness b^*, hue angle h^*, and chroma C^* changes during the rehydration of dried apples.

Variable	SSE	R^2	Adjusted R^2	RMSE
L^*	0.0077–0.2359	0.6306–0.9889	0.6306–0.9889	0.0394–0.2068
b^*	0.0009–0.5514	0.3516–0.9986	0.3516–0.9986	0.0177–0.3031
h^*	0.0105–0.6388	0.2601–0.9865	0.2601–0.9865	0.0419–0.3574
C^*	0.0012–0.6660	0.3611–0.9980	0.3611–0.9980	0.0241–0.3085

The following results of investigation of the effects of characteristic dimension L, drying air temperature T_d, drying air velocity v_d, and rehydration temperature T_r on the first-order model constant k_c were obtained:

- for lightness L^*

$$k_c = 1.452388 + 0.028556 v_d - 0.0004 {T_d}^2 - 0.00477 {v_d}^2 + 0.016592 L T_d, \tag{25}$$

- for yellowness b^*

$$k_c = 0.00951, \tag{26}$$

- for hue angle h^*

$$k_c = 0.077, \tag{27}$$

- for chroma C^*

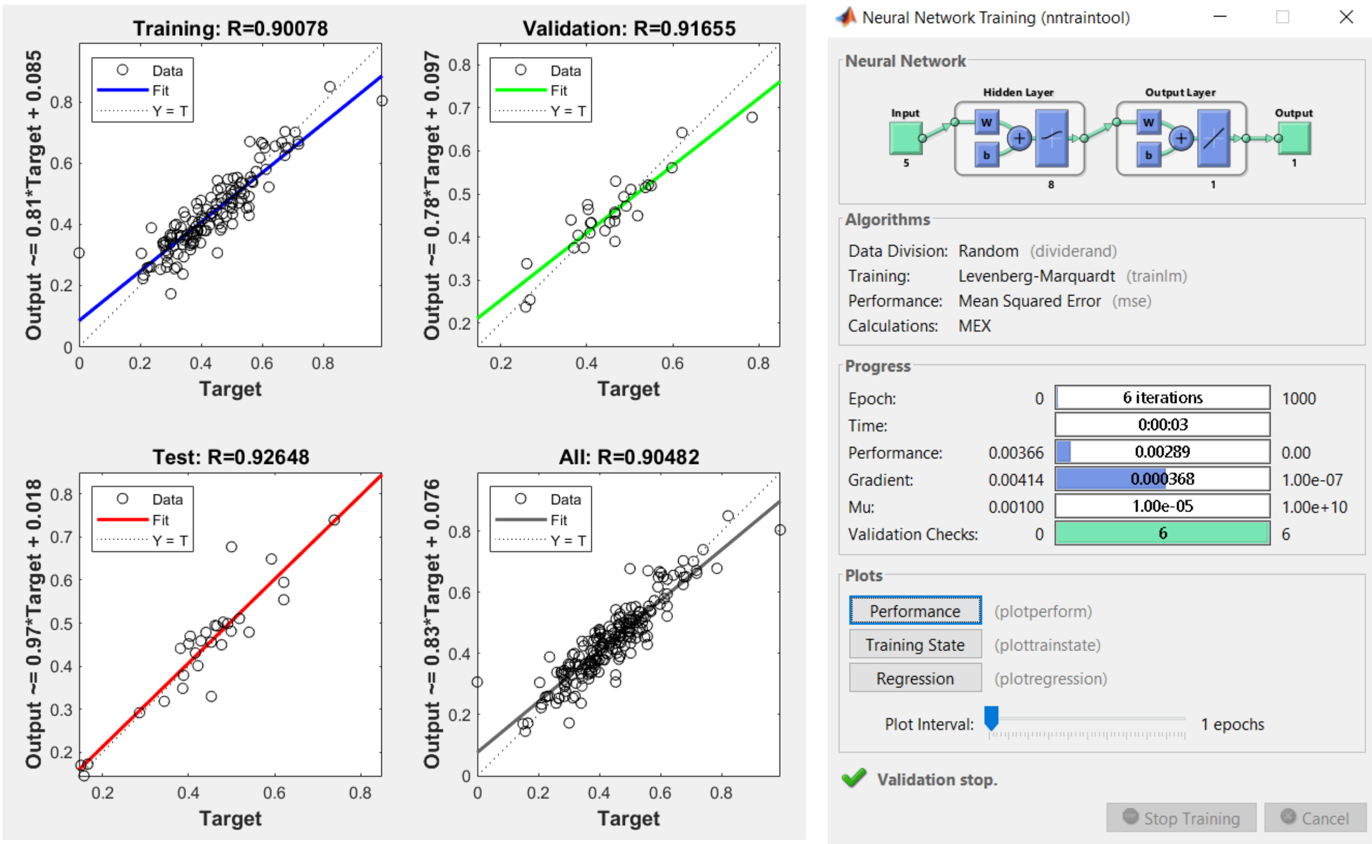
$$k_c = -0.16013 + 0.001343 L T_d. \tag{28}$$

It can be stated that the rate colour degradation for lightness and chroma depended in a statistically significant manner on characteristic dimension and on drying conditions (on T_d and v_d for L^* and only on T_d for C^*), and depended in a statistically insignificant way on rehydration conditions. Dependence of the rate colour degradation for yellowness and hue angle on both drying and rehydration conditions and on characteristic dimension was, on the other hand, statistically insignificant. The degradation of b^* indicated the occurrence of Maillard reaction, responsible for nonenzymatic browning [77].

The colour variation ΔE was predicted with ANN. MLP 5-8-1 was in this study (Figure 5). The *logsig* transfer function in hidden layer and *purelin* transfer function in output layer and *trainlm* training function (L-M) and *learngdm* adaptation function were used. The R value was equal to 0.9166 (for validation set). Weights and biases between input and hidden layer and between hidden and output layers for this ANN are given in Table 10.

Table 10. Weights and biases between input and hidden layer and between hidden and output layers for the colour variation ΔE.

No.	Weights and Biases between Input and Hidden Layer						Weights and Biases between Hidden and Output Layer	
	Weights					Bias	Weights	Bias
i	D_{1i}	D_{2i}	D_{3i}	D_{4i}	D_{5i}	D_i	W_i	B_i
1	−0.3936	0.068912	7.7881	−0.37068	−0.29036	−4.083	9.4829	4.3014
2	5.5244	3.3242	0.99513	−1.4537	−2.1599	1.3043	−1.7557	
3	5.143	−0.15515	5.6857	−2.9232	−7.4673	0.73944	−3.9588	
4	−0.67089	−5.7064	2.1326	0.36501	2.9711	0.87002	−3.3684	
5	−4.0698	3.8803	2.1008	1.5752	3.0415	0.7498	1.5977	
6	2.7802	5.5689	3.5537	−2.3719	−3.6688	−1.6085	−2.9859	
7	0.13428	−0.70078	0.3338	−7.8718	1.8079	−0.83412	4.0532	
8	7.6823	0.47277	−0.4144	8.8348	6.2643	−0.78616	5.2191	



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

Figure 5. The best ANN goodness of fit and correlation coefficients R between ANN and output (**a**), and window of neural network training (**b**) for the colour variation ΔE.

In the backward stepwise method used in the presented work, for the colour variations ΔE, five models were generated, taking only four of the variables (parameters) as inputs. The variable not taken into account for which the resulting models gave the highest value of error was considered to be the most important one. Table 11 presents the backward stepwise results in which five models were generated by applying four of the discussed variables. The values of R, RMSE, R^2, adjusted R^2, and SSE of each generated model are shown in Table 11. The discussed table also shows the results of statistical analyses on the modelling of colour variations ΔE.

Table 11. Sensitivity analysis for the colour variation ΔE—stepwise method.

Parameter / Statistical Test Method	All Parameters Considered	Omitted L	Omitted T_d	Omitted v_d	Omitted T_r	Omitted t
R	0.9048	0.1395	0.4424	0.4482	0.4859	0.6721
RMSE	0.0567	0.2654	0.2953	0.1980	0.1246	0.1022
R^2	0.8187	0.0195	0.1957	0.2009	0.2361	0.4517
Adjusted R^2	0.8177	0.0143	0.1915	0.1967	0.2321	0.4488
SSE	0.0573	0.1332	0.1207	0.1203	0.1176	0.0996

It is shown from the conducted research that all of the ANNs applied in this work predicted the behaviour of colour variators quite acceptably. As can also be seen from the obtained results, the characteristic dimension L of apples had the greatest impact on the colour variations (only for RMSE did it occupy the second position). The drying air temperature took the second position. The drying air temperature took second place (with the exception of RMSE being in first place), and then, successively, drying air velocity held the third position, and the rehydration temperature was in fourth place. Time (the duration of the rehydration process) had the least influence on colour variations.

Due to complex biochemical reactions and water loss in the drying process come adverse changes in product quality, whereas these changes are dependent also on the drying regime. Due to the high content of water, sugars (glucose, fructose), and the presence of pectins and malic acid, the discussed product quality changes apply especially to apples [77]. The apple colour change could be associated with the synthesis of phenolic compounds, the non-enzymatic browning reactions [78], the decomposition of original pigments, the formation of brown pigments (by enzymatic and non-enzymatic browning reactions), and other undesirable pigments (pigments responsible for the original colour: chlorophyll (green), carotenoids, flavonoids (yellow), anthocyanins (red)) [79]. The Maillard reaction occurs in wet products during thermal processing and resulted from the structural shrinkage, which subsequently increases the opacity of dried products [80].

4. Conclusions

The Page and the modified Page model can be considered to be the most appropriate to characterise the mass gain (adjusted R^2 = 0.9520–0.9980, RMSE = 0.0143–0.0619) and the volume increase (adjusted R^2 = 0.8598–0.9982, RMSE = 0.0142–0.1130), whereas the Peleg, Pilosof–Bouquet–Batholomai, and Singh and Kulshrestha models are the most appropriate to characterise dry matter loss (adjusted R^2 = 0.9299–0.9974, RMSE = 0.0116–0.0454) during the rehydration of dried apples. The proposed ANNs (MLP4-4-1, MLP4-4-1, MLP4-3-1, and MLP5-8-1) describe rehydration indices (RI_1, RI_2, WAC) and colour variation (ΔE) satisfactorily (R = 0.9048–0.9423, RMSE = 0.0567–0.0802). A sensitivity analysis of ANN (backward stepwise method) showed that the characteristic dimension has the greatest influence on the considered indices and ΔE. The first-order model can be applied only for rough estimation of lightness, yellowness, hue angle, and chroma changes during rehydration of dried apples. Dying conditions influence only the rate of lightness and chroma degradation, whereas rehydration conditions do not influence the degradation rate of any investigated colour parameter.

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