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Modelling of dried apple rehydration indices using ANN**

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A b s t r a c t. The purpose of the research was to study the effect of different drying and rehydration conditions on the rehydration indices of apple and to model the rehydration indices of apple using artificial neural networks. The research involved the examination of the rehydration process of 10 mm apple cubes, which were dried in natural convection (drying air velocity), forced convection and fluidization at the following drying temperatures 50, 60 and 70°C. The process of rehydration was conducted in distilled water at the following temperatures 20, 45, 70 and 95°C. Five rehydration indices were used to express rehydration. Artificial neural networks (MLP 3-5-1 and MLP 3-4-1) were used to make the rehydration indices dependent on both drying and rehydration parameters: drying temperatures, *v* and following temperatures. Five statistical tools, *i.e.* correlation coefficient, mean bias error, root mean square error, reduced chi-square, and t-statistic method (*t*-stat), were applied to determine the fit. To identify critical parameters and their impact on the ANN outputs, a sensitivity analysis (backward stepwise method) was performed.

K e y w o r d s: rehydration, rehydration indices, apple, quality, ANN

INTRODUCTION

Drying is the most popular method for the preservation of agricultural products such as fruit, vegetables, herbs or spices, as it ensures the microbiological safety of various biological materials. This method has several disadvantages and limitations. Contact between the material being dried and hot air causes the degradation of key flavour compounds and nutritional substances. Besides, there is also a risk of volatile compound separation during the drying process (Silva *et al.,* 2017). Undesirable changes in product colour, possibly due to Maillard reactions, may be observed in the food materials being processed (Figiel *et al.,* 2010). Numerous researchers have attempted to study the influence of drying on the quality of various agricultural products, thereby confirming the importance of additional thorough studies in this area (Karam *et al.,* 2016).

Dehydrated products may be used in many processed or ready-to-eat foods instead of fresh foods due to such advantages as the convenience of transportation, storage, preparation and use. Some dehydrated products must be rehydrated before consumption or further processing (Nayak *et al.,* 2006).

Rehydration is the process of moistening dry material. Three main processes take place simultaneously during rehydration: imbibition of water into the dried material, swelling of the material and leaching of solubles (Moreira *et al.,* 2008). It is a very complex phenomenon that involves different physical mechanisms such as water imbibition, internal diffusion, convection at the surface and within large open pores, as well as the loosening of the solid matrix. Capillary imbibition is very important during the early stages, leading to an almost instantaneous uptake of water. Tension effects between the liquid and the solid matrix may also be relevant. In the rehydration process, two main crosscurrent mass fluxes occur, a water flux from the rehydrating solution to the product, and a flux of solutes (sugars, acids, minerals, vitamins) from the food product to the solution, with the kinetics depending on the immersion medium (Górnicki *et al.,* 2013).

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Some of these factors induce changes in the structure and composition of the plant tissue, which results in the impairment of the reconstitution properties. Therefore, equilibrium moisture content at saturation does not reach the moisture content of the raw materials prior to dehydration, indicating that the dehydration procedure is irreversible. Physical and chemical changes that take place during drying affect the quality of the dehydrated product, and merely by the simple addition of water, the properties of the raw material cannot be restored. Rehydration cannot be simply treated as the reverse process of dehydration. Hence, rehydration may be considered as a measure of the damage to the material caused by drying and the treatment preceding dehydration (Witrowa-Rajchert, 1999).

The process of rehydration is one of the most important quality properties of dried products, and should be rapid and complete. The fact that some dehydrated products are eventually consumed rehydrated, *e.g.* in milk, yoghurt, fruit juices, sucrose or glucose solutions or in instant soups and ready to eat meals, is another important reason for studying food rehydration processes, due to the importance of these processes in the development of these kinds of products (Maldonado *et al.,* 2010). The achievement of a better understanding of rehydration processes seems to be crucial for the quality improvement of both dehydrated and rehydrated products, as well as for the production of new products (Seguí *et al.,* 2013). Many researchers claim that the drying method used has the most significant impact on the rehydration process (Benseddik *et al.,* 2018; Lewicki and Wiczkowska, 2006; Said *et al*., 2015; Stępień, 2008).

Rehydration is influenced by intrinsic factors: product chemical composition, pre-drying treatment, drying techniques and conditions, post-drying procedure, *etc*., and extrinsic factors: the composition of the immersion media, temperature and hydrodynamic conditions (Rastogi *et al.,* 2004). A knowledge of the rehydration kinetics of dried products is important for the optimization of processes in terms of quality, since rehydration is a key quality aspect for the dried products that have to be reconstituted before their consumption (Garcia-Pascual *et al.,* 2006). Rehydration indices and mathematical models of the rehydration process (empirical, semi-empirical, and theoretical) are reviewed and systematized (Górnicki, 2011).

A cluster analysis is a set of different algorithms, which group objects into clusters. Methods of cluster analysis are used in the data-mining phase when there are no *a priori* hypotheses. In the cluster analysis phase, two algorithms were used, *i.e*., the *k*-means algorithm, and the EM (Expectation-Maximization or Estimation-Maximization) algorithm. The foundation of the *k*-means algorithm (Hartigan, 1975) is relatively simple: given the specified number (desirable or hypothetically assumed) of *k* clusters, the observations are assigned to clusters so that the means in the clusters differ as much as possible from one another in terms of distance. The methods applied in generalized cluster analysis using EM methods (Witten and Frank, 2005) constitute the extension of the above approach. Instead of assigning cases (observations) to clusters so that the differences between the means (quantitative variables) in groups are as great as possible, the EM algorithm calculates the probability of belonging to clusters assuming one or more probability distributions. The goal of the EM algorithm is the maximization of the overall probability (data credibility) for a given division into clusters, and, as opposed to the classic interpretation of *k*-means, the algorithm may be applied both for quantitative and qualitative variables.

An artificial neural network (ANN) is an information processing system, which learns from input/output data to determine the relationships between input/output data, and is used in pattern recognition, classification, *etc*. Unlike other modelling techniques (*i.e.* differential equations and regression equations), an ANN can handle more than two variables to predict two or more outputs. Regression equations or statistical models are subject to assumptions and cautions inherent in the analyses. ANNs are capable of correlating large and complex data sets. ANNs are used for their learning or adapting ability, and they do not require much knowledge of the underlying relationships between their input and output variables. The network learns both from the input and data, repeatedly. It can also approximate any continuous or discontinuous linear or nonlinear function. Therefore, such networks are very useful for modelling certain processes that are not yet completely understood (Mittal, 1996). Winiczenko *et al.* (2018) used a genetic algorithm and response surface methodology to optimize an ANN topology for predicting the colour change in rehydrated apple.

A disadvantage of artificial neural networks is the difficulty in the interpretation of the results it produces. The reliability of artificial intelligence often depends on its ability to explain the results obtained. Several methods have been proposed to overcome this disadvantage. These methods, *i.e.* sensitivity analysis (SA), are used to determine the degree of "sensitivity" of a given ANN to changes in the value of its parameters and its structure. Sensitivity coefficients describe changes in the ANN's outputs due to variations in the input parameters. A large sensitivity suggests that the ANN's performance can drastically change as a result of a small variation in a parameter. There are a few methods used to study the sensitivity of the ANN, for example: the "stepwise" method (Forward stepwise, Backward stepwise, Improved stepwise) (Gevrey *et al.,* 2003), the "PaD" method (Dimopoulos *et al.,* 1995), the "Profile" method (Lek *et al.,* 1996), the "Weight" method (Garson, 1991).

The main aim of this work was to study the effect of different drying and rehydration conditions on the rehydration indices of apple, and to model the rehydration indices of apple using artificial neural networks.

MATERIALS AND METHODS

Fresh, high-quality (Ligol) apples were purchased from a local store in Warsaw, Poland. Just before the drying experiments commenced, the apples were peeled, and the outer cortex was cut into cubes with thicknesses of 10±1 mm. The initial moisture content of the fresh apple samples was approx. 85% w.b. (5.66 d.b.).

The following techniques were used to dry the raw material: natural convection with drying air velocity: $v = 0.01$ m s^{-1} (chamber dryer), forced convection with $v = \{0.5$ m s^{-1}, 2 m s$^{-1}\}$ (tunnel dryer) and fluid bed drying with $v = 6$ m s^{-1} (laboratory-fluidized bed dryer) (Górnicki and Kaleta, 2007; Kaleta and Górnicki, 2010b; Kaleta *et al.,* 2013b). The drying experiments were carried out at drying air temperatures T_d=50, 60 and 70°C (the driers had an electric heater) in three replications until a constant mass of dried material was reached. The equilibrium moisture content of dried samples was about 9% w.b. (0.098 d.b.). The samples obtained from three independent drying experiments under the same drying conditions were randomly mixed, which produced 12 sample batches ($T_d = \{50, 60, 70\} \times v = \{0.01, 0.5, 2, 6\}$). Each batch was stored for further studies in a tightly sealed container (not exposed to sunlight) for about one week at 20°C.

The rehydration of dried apple was conducted in distilled water at temperature T_r = 20, 45, 70, and 95°C. Rehydration lasted from 6 h (at a medium temperature amounting to 20°C) to 2 h (for 95°C), and was carried out in triplicate. The initial mass of each dried sample subjected to rehydration was 10 g, and the dried sample mass to water mass ratio at the beginning of the rehydration process was 1:20 (such a ratio was used very frequently in the literature (Femenia *et al*., 2000; Ravindra and Chattopadhyay, 2000; Winiczenko *et al.*, 2018)). The water temperature was constant, and it was not stirred during rehydration.

The following indices were used to express rehydration.
– Index RI_1:

$$RI_1 = \frac{\text{mass of material after rehydration}}{\text{mass of dried material}}. \quad (1)$$

Index RI_1 is the most common one used to describe rehydration characteristics. This index has been applied to describe the rehydration of amla (Verma and Gupta, 2004), apples (Jokić *et al.,* 2009), button mushrooms (Askari *et al.,* 2009), celery (Nowak *et al.,* 2016), garlic (Sharma and Prasad, 2006), hawthorn fruits (Aral and Beşe, 2016), jackfruit (Kaushal and Sharma, 2016), kiwi (Ergűn *et al.,* 2016), lablab bean (Pervin *et al.,* 2008), potatoes (Ravindra and Chattopadhyay, 2000), pumpkin (Seremet (Ceclu) *et al*., 2016), sea cucumbers (Zhang *et al.,* 2016), soybean curd (Harnkarnsujarit *et al.,* 2016), wormwood leaves (Beigi, 2017), and yam (Lin *et al.,* 2007).
– Index RI_2:

$$RI_2 = \frac{\text{mass of material after rehydration}}{\text{mass of raw material}}. \quad (2)$$

This index has been applied to describe the rehydration of apple, parsley, potato (Lewicki 1998), cauliflower (Jayaramann *et al*., 1990), cabbage, carrot, celery, cucumber, eggplant, green onion, sword bean, horse radish, pepper, tomato (Zhang *et al*., 1994), chicken meat (Farkas and Singh, 1991).
– Index RI_3:

$$RI_3 = \frac{\text{mass of water absorbed during rehydration}}{\text{mass of dried material}}. \quad (3)$$

Index RI_3 has been applied to describe the rehydration of apples, kiwifruits, and tomatoes (Redgewell *et al*., 2008), bananas (Maskan, 2000), carrots (Doymaz, 2017), Chinese jujube (Fang *et al*., 2009), kiwifruits (Ergűn *et al*., 2016), longan fruit (Nathakaranakule *et al*., 2010), potatoes (Cheng *et al*., 2006), and sweet potatoes (Antonio *et al*., 2008).
– Index RI_4 (formulated by the authors):

$$RI_4 = \frac{\text{mass of water in rehydrated material}}{\text{mass of water in the raw material}}, \quad (4)$$

– water absorption capacity WAC:

$$\text{WAC} = \frac{m_r(100 - s_r) - m_d(100 - s_d)}{m_o(100 - s_o) - m_d(100 - s_d)}, \quad (5)$$

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

The WAC index was proposed by Lewicki (1998) and has been widely used to describe the rehydration of apples, parsley, and potatoes (Lewicki, 1998), apples (Atarés *et al*., 2008), carrots (Markowski and Zielińska, 2011), chestnuts (Moreira *et al*., 2008), mangoes (Link *et al.,* 2017), *Morchella esculenta* (morel) (Garcia-Pascual *et al.,* 2006), mushrooms (Garcia-Pascual *et al.,* 2005), potatoes (Markowski *et al.,* 2009), sesame seeds (Khazei and Mohammadi, 2009), and tomatoes (Lewicki *et al.,* 2002).

The goal of the research was to analyse the impact of selected factors of the drying and dehydration process of selected products (T_d, v, T_r) being studied on the quality indices (rehydration indices) of these products. Therefore, the results were searched to find cases that shared common factors according to their similarity with regards to the factors being analysed and the selected quality index.

The significance of the impact of T_d, v and T_r on the rehydration indices was determined using analysis of variance after accepting the uniformity test of Levene's variance. The Tukey test HSD was applied to divide the results into uniform groups (at the significance level of $p = 0.05$). Calculations were carried out using the Statistica 12.5 application.

ANN modelling was carried out with Matlab R2015a. The rehydration indices were predicted with feedforward multilayer perceptron artificial neural networks. In this study, the cases (the number depends on the index) were randomly divided into the following sets: for training - 70% cases, for validation - 15% cases and for testing - 15% cases. Inputs: T_d, v, T_r were normalized to obtain values within the range 0-1. The values of the drying temperature, drying air velocity, rehydration temperature were normalized by dividing them by 70, 6, and 95, respectively. The values of the rehydration indices (output) RI_1 and RI_3 were divided by 5 and 4, respectively.

Statistical methods were used in order to find the most suitable model for the prediction of the rehydration indices of apple. The most frequently used of the statistical criteria from the literature for selecting the most suitable model are given below:

– Correlation coefficient R:

$$R^2 = \frac{\sum_{i=1}^{N}\left(X_i - X_{p,i}\right)\cdot\sum_{i=1}^{N}\left(X_i - X_{e,i}\right)}{\sqrt{\left[\sum_{i=1}^{N}\left(X_i - X_{p,i}\right)^2\right]\cdot\left[\sum_{i=1}^{N}\left(X_i - X_{e,i}\right)^2\right]}}, \tag{6}$$

where: $X_{p,i}$ – is the i-th predicted value, $X_{e,i}$ – is the i-th experimental value, N is the number of the observation.

The closer R is to 1, the closer the relationship between the experimental and the predicted values. The discussed coefficient has been used by *e.g.* (Kaushal and Sharma, 2016):

– Mean bias error MBE:

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(X_{p,i} - X_{e,i}\right). \tag{7}$$

The lower the values of MBE, the better the fit. This criterion has been used by *e.g.* (Kaleta and Górnicki, 2010a).

– Root mean square error RMSE (root mean square deviation RMSD):

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(X_{p,i} - X_{e,i}\right)^2\right]^{1/2}. \tag{8}$$

Lower RMSE values indicate the better fit of the model. The root mean square error has been considered by *e.g.* (Beigi, 2017; Kaleta *et al.,* 2013b):

– Reduced chi-square χ^2:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(X_{e,i} - X_{p,i}\right)^2}{N-n}, \tag{9}$$

where n is the number of constants.

The lower the values of χ^2, the better the fit. The discussed coefficient has been applied by *e.g.* (Aral and Beşe, 2016):

– *t*-statistic:

$$\text{t-stat} = \left[\frac{(n\text{-}1)MBE^2}{RMSE^2\text{-}MBE^2}\right]^{1/2}. \tag{10}$$

The smaller the criterion value, the better the model performance. *T*-stat has been considered by *e.g.* Kaleta and Górnicki (2010b).

To identify critical parameters and their degree of impact on the ANN outputs, a sensitivity analysis was performed. One of the most important methods in sensitivity analysis is the backward stepwise method, which consists of step-by-step adding or rejecting one input variable, and examining the effect on the output results. For instance, the largest value in RMSE or χ^2 due to one input omission shows the most important input (Gevrey *et al.,* 2003).

RESULTS AND DISCUSSION

Cluster analysis with the EM or *k*-means algorithm was used in the research, depending on the cluster size, *i.e.* the method capable of finding a larger cluster, was selected. The clusters found (one for each index) had high correlation coefficients (above 0.9). The cluster for the index RI_1 includes the cases, in which $T_d \in$[50-70°C], $v \in$[0.01-2 m s^{-1}], $T_r \in$[20-95°C]. Clusters for indices RI_2, RI_3 and RI_4 include all cases, in which $T_d \in$[50-70°C], $v \in$[0.01-6 m s^{-1}], $T_r \in$[20-95°C], while the cluster for the WAC index includes the cases, in which $T_d \in$[50-70°C], $v \in$[2-6 m s^{-1}], $T_r \in$[20-95°C].

Table 1 shows the parameters of the drying and rehydration processes (T_d, v, T_r) which produced the highest values of rehydration indices: RI_1, RI_2, RI_3, RI_4 and WAC. The apples dried in the tunnel dryer (v=2 m s^{-1}) at 70°C and then rehydrated in distilled water at 70°C were characterized by the highest values of RI_1, RI_2, and RI_3: 4.59, 0.55, and 3.59, respectively. Dried apples obtained from the tunnel dryer (v=0.5 m s^{-1}) at 70°C and then rehydrated at 45°C had the highest value of RI_4 (0.55), whereas for apples dried in a fluidized bed (v=6 m s^{-1}) at 60°C and rehydrated at 70°C the value of WAC was the highest with a value of 0.50.

Figures 1-3 show the impact of T_r, T_d and v on the following rehydration indices: RI_1, RI_2, RI_3, RI_4 and WAC. Parameter v indicates the drying method.

Indices RI_1 and RI_2 are defined as the ratio of rehydrated material mass (the mass of the material following rehydration) to the mass of dried material and the material prior to drying, respectively (Eqs (1) and (2)). Irrespective of the drying method examined in the work, the obtained dried

Table 1. Parameters of drying and rehydration processes, which produced the highest values of rehydration indices

Rehydration index	Parameters of drying and rehydration processes		
	T_d	v	T_r
RI_1	70	2	70
RI_2	70	2	70
RI_3	70	2	70
RI_4	70	0.5	45
WAC	60	6	70

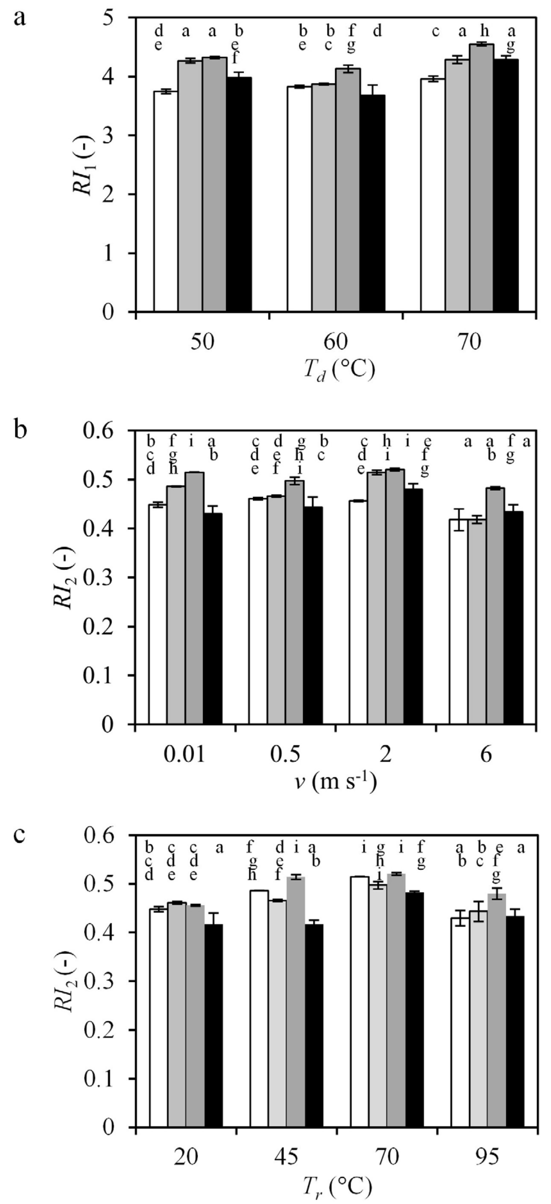

Fig. 1. Rehydration indices RI_1 and RI_2 for apple: a) dried at v=0.5 m s^{-1}, where: ☐ -T_r=20°C, ■ -T_r=45°C, ■ -T_r=70°C, ■ -T_r=95°C; b) dried at T_d=60°C, where: ☐ -T_r=20°C, ■ -T_r=45°C, ■ -T_r=70°C, ■ -T_r=95°C; c) dried at T_d=60°C, where: ☐ -v=0.01 m s^{-1}, ■ -v=0.5 m s^{-1}, ■ -v=2 m s^{-1}, ■ -v=6 m s^{-1}. The same letters indicate homogenous groups ($p<0.05$).

material had a similar moisture content (and, consequently, mass). However, the drying method affected the extent of degradation changes and the drying temperature at the time when these changes occurred during the drying process (Lewicki and Wiczkowska, 2006). Therefore, the value of the indices being discussed is predominantly influenced by the mass of the obtained rehydrated material. 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 magnitude of the degradation changes during drying but also on the conditions of the rehydration process. Increasing the rehydration temperature causes deterioration in the texture of the fruit, which compounds the damage caused during thermal dehydration and promotes a significant loss in the mechanical resistance of the samples. This excessive softening of the tissues alters the mass transfer ability of the system (Maldonado *et al.*, 2010). Consequently, the nature of the influence of the drying parameters and rehydration on the indices RI_1 and RI_2 being discussed is consistent with previously published results.

The impact of the drying temperature on indices RI_1 and RI_2 is not unequivocal (Fig. 1a). The increase in the drying temperature from 50 to 70°C results in an increase of the rehydration indices being discussed. However, the initial increase in T_d from 50 to 60°C did not have any impact (*e.g.* for T_r=20°C) or even result in a decrease (*e.g.* for T_r=45°C) in the values of these indices. Further increases in the drying temperature (to 70°C) resulted in an increase in the values of these indices, and they then reached the highest values. Jokić *et al.* (2009) stated that for rehydration at 20°C for dried apple (Florina) an increase in T_d (from 50 to 70°C) resulted in a decrease of RI_1.

The increase in the rehydration temperature to 70°C resulted in an increase in both the RI_1 and RI_2 indices (Fig. 1a,b). However, a further increase in T_r to 95°C resulted in a decrease in the values of these indices, which even then reached values similar to those obtained at T_r=20°C (*e.g.* T_d=60°C).

The drying air velocity does not have an unequivocal impact on both the RI_1 and RI_2 index (Fig. 1c). The increase in the flow of the drying air from 0.01 to 2 m s^{-1} did not have an impact on the indices being discussed (*e.g.* for T_r=20°C) nor did it influence their increase (*e.g.* for T_r=95°C). However, the values of the indices (*e.g.* for T_r 20, 45°C) were the lowest for the rehydrated dried material obtained from the fluidized bed drier (v=6 m s^{-1}). Jokić *et al.* (2009) stated that for dried apple (Florina) rehydrated at 20°C an increase in v (from 1.5 to 2.75 m s^{-1}) resulted in an increase in RI_1.

Indices RI_3 and RI_4 are defined as the ratios of the mass of water absorbed in the rehydration process and the mass of water in the rehydrated material (the sum of the mass of water absorbed in the process of rehydration (this mass depends on the extent of degradation changes during drying but also on the conditions of the rehydration process (Maldonado *et al.*, 2010)) and on the mass of water in the dried material) compared to the mass of the dried material and the mass of water in the material prior to drying, respectively (Eqs (3) and (4)). Similarly, as in the case of indices RI_1 and RI_2, the values of indices RI_3 and RI_4 are predominantly influenced by the mass of the absorbed water. Therefore, the influence of the drying parameters and rehydration on indices RI_3 and RI_4, is analogical.

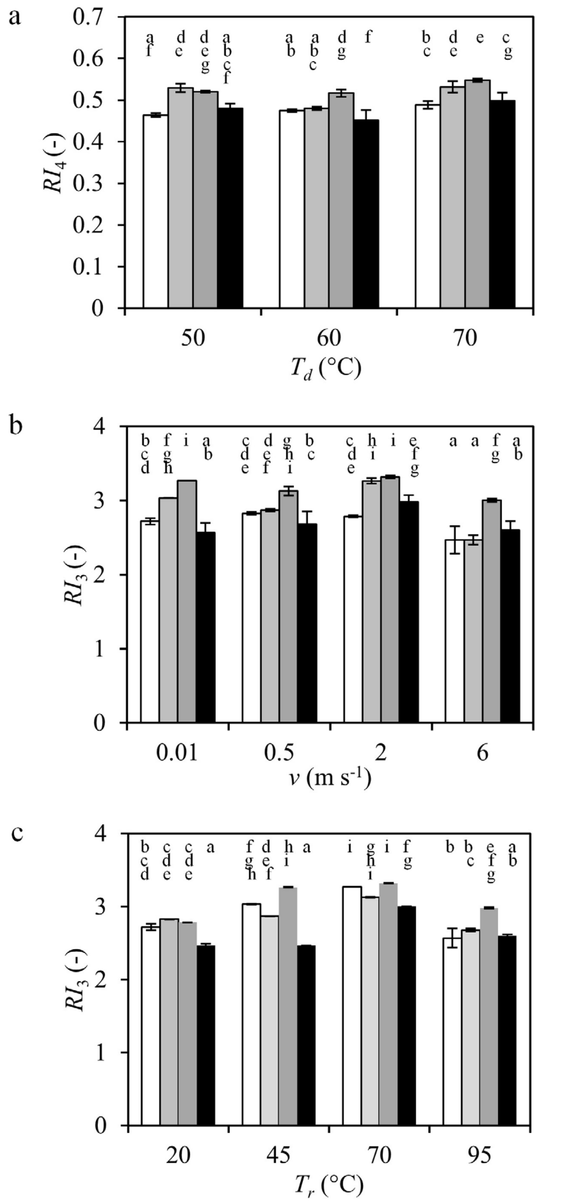

Fig. 2. Rehydration indices RI_3 and RI_4 for apple: a) dried at v=0.5 m s^{-1}, b) dried at T_d=60°C, c) dried at T_d=60°C. Explanations as in Fig. 1.

The impact of the drying temperature on indices RI_3 and RI_4 is not unequivocal (Fig. 2a). The increase in the drying temperature from 50 to 70°C results in an increase in the rehydration indices being discussed. However, the initial increase in T_d from 50 to 60°C did not have any influence (*e.g.* for T_r=20°C) or even resulted in a decrease (*e.g.* for T_r=45°C) in the values of these indices. Further increases in the drying temperature (to 70°C) resulted in an increase in the values of these indices, which then reached their highest values.

An increase in the rehydration temperature to 70°C resulted in an increase in both the RI_3 and RI_4 indices (Fig. 2a, b). However, a further increase in T_r to 95°C resulted in a decrease in the values of these indices, which even then reached values similar to those obtained at T_r=20°C (*e.g.* T_d=60°C).

Drying air velocity does not have an unequivocal impact on both the RI_3 (Fig. 2c) and RI_4 index. An increase in the flow of the drying air from 0.01 to 2 m s^{-1} either did not have any impact on the indices being discussed (*e.g.* for T_r=20°C) or resulted in their increase (*e.g.* for T_r=95°C). However, the values of the indices obtained in the process of rehydration of previously dried material from the fluidized bed drier (v=6 m s^{-1}) were generally lower (especially for smaller T_r: 20, 45°C) than for the dried material obtained from other driers used in the study.

The WAC rehydration index (Eq. (5)) is defined as the ratio of the mass of water absorbed in the process of rehydration to the mass of water removed from the material in the process of drying. Obtaining a value of WAC=1 means that the same amount of water that was removed from the material during drying was absorbed during rehydration. The WAC rehydration index depends on both the rehydration temperature and the drying air velocity. The increase in the rehydration temperature resulted in an increase in the WAC index or did not cause any changes in the index (Fig. 3) within the rehydration temperature range 20-70°C. Similarly, as in the case of the rehydration indices

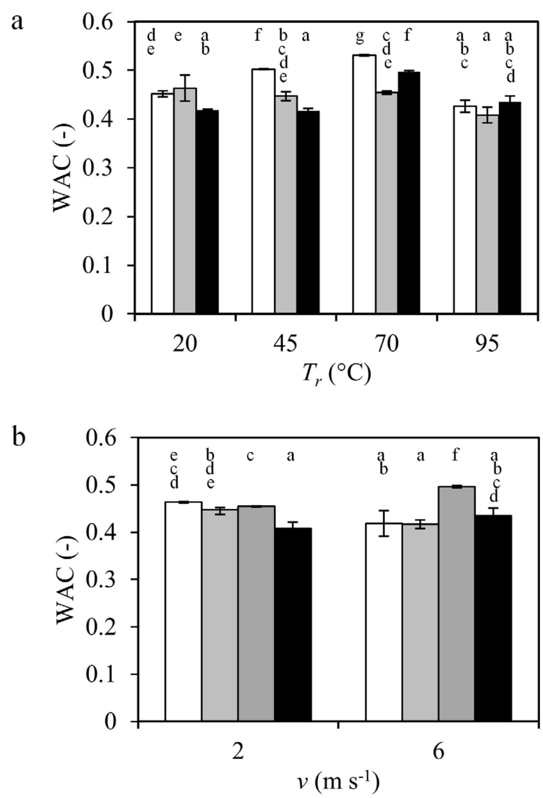

Fig. 3. WAC rehydration index for apple: a) dried at T_d=60°C, where: □ -v=0.01 m s^{-1}, ■ -v=2 m s^{-1}, ■ -v=6 m s^{-1}; b) dried at T_d=60°C, where: □ -T_r=20°C, ■ -T_r=45°C, ■ -T_r=70°C, ■ -T_r=95°C. The same letters indicate homogenous groups (p<0.05).

(RI_1-RI_4) discussed above, for the highest examined rehydration temperature (T_r=95°C), this index reached a lower value (statistically significant differences $p < 0.05$) than for T_r = 70°C and T_r = 20°C (with the exception of the rehydration of the material dried in the fluidized bed drier). Lewicki (1998) obtained a slightly lower value of WAC (compared to the one obtained in this work): 0.396.

Kaleta *et al.* (2013a) did not reveal the statistically significant impact of the drying temperature on the loss of dry mass of the material, or the impact of the selected drying method (free convection, forced convection, fluidized bed drying) on the final value of the dry mass loss of dried apples as a result of rehydration. For the rehydration of apples of the *Idared* variety, Witrowa-Rajchert (2003), dried them using three methods, *i.e.* convection, convection-microwave, and freeze-drying showed that the lowest dry mass loss was observed for apples dried using the sublimation method, for the two other drying methods similar results were obtained. Cubes of apples of the Gala variety, dried using the combined method, which involves initial drying by convection, and a further drying process using the microwave-vacuum method, demonstrated a greater capacity to retain dry mass than the apples dried using the convection method (Figiel, 2007). Rząca (2009) did not reveal significant differences in dry mass loss during the rehydration of apples of the Idared variety, dried using the following methods: convection, microwave-convection, and radiation-convection. Jokić (2009) observed that at the air velocity of 2.75 m s^{-1}, the rehydration ratio *vs*. different drying temperatures (50, 70°C) was higher compared to that at the air velocity of 1.5 m s^{-1}. Statistical analysis showed, however, that a drying temperature of 60°C for the selected air velocities had no statistically significant influence on the rehydration ratio ($p < 0.05$).

Mass increment of dried apples during rehydration depends on the rehydration temperature (Kaleta *et al.,* 2014). The higher the temperature, the faster the increment and the higher the final mass of the sample after rehydration. Simultaneously, at a temperature of 95°C, the final mass of the rehydrated sample is similar to the final mass of the sample rehydrated at a temperature of 45°C. The lowest final loss of dry substance was recorded for dried apples rehydrated at a temperature of 20°C, while for samples rehydrated at T_r 45, 70 and 95°C the values of the final dry substance loss were similar. The influence of the rehydration temperature on the process of rehydration, and, consequently, on the values of the rehydration indices, may be attributed to an increase in diffusion intensity with temperature (Górnicki, 2011).

Witrowa-Rajchert and Lewicki (2006) compared the volume increase with mass gain during the rehydration of apple, carrot, and potatoes. They stated that the mechanism of water imbibing is substantially influenced by the porosity and chemical composition of the dried material. If the material is characterized by a high degree of porosity then water should fill the pores and the gain in its volume should be either low or entirely absent. In the case of low porosity, and the presence of biopolymers, water penetrating into the matrix of a solid causes swelling and an increase in the volume of the material. Hence, the process of water absorption during rehydration consists of filling the air spaces formed upon drying or in penetrating into the matrix of a solid body, depending on the type of the material used, namely its chemical composition. Dried apples are very porous, hence their mass gain is much faster than the volume increase. The absorption of water by polymers was demonstrated. A more rapid gain in mass than volume lead to a rapid dissolution of low-molecular weight compounds, which may be in an amorphous state, and to a structural collapse at the initial stages of the rehydration process. Amorphous regions of the solid components are the most accessible to the rehydrating medium (Lewicki *et al.,* 1997).

MLP 3-5-1 and MLP 3-4-1 were used to describe all tested rehydration indices RI_1, RI_2, RI_3, RI_4, and the WAC rehydration index, respectively (Table 2). Hidden and output layers with a log-sigmoid transfer function (“logsig”) (hidden layer for RI_1, RI_3, RI_4, WAC):

$$\mathrm{F}(x) = \frac{1}{1 + \exp^{-\beta x}}, \tag{11}$$

hyperbolic tangent sigmoid transfer function (“tansig”) (hidden layer for RI_2 and output layer for RI_1, RI_3, WAC):

$$\mathrm{F}(x) = \frac{2}{1 + \exp^{-\beta x}} - 1, \tag{12}$$

linear transfer function (“purelin”) (output layer for RI_2, RI_4):

Table 2. Parameters of neural networks describing rehydration indices

Rehydration index and ANN form	Regression coefficient R			Transfer function	
	training set	test set	validation set	hidden layer	output layer
RI_1, MLP 3-5-1	0.9530	0.9665	0.9882	logsig	tansig
RI_2, MLP 3-5-1	0.9462	0.9721	0.9584	tansig	purelin
RI_3, MLP 3-5-1	0.9528	0.9478	0.9370	logsig	tansig
RI_4, MLP 3-5-1	0.9347	0.9347	0.9571	logsig	purelin
WAC, MLP 3-4-1	0.9493	0.9395	0.9499	logsig	tansig

$$F(x) = ax + b\,, \qquad (13)$$

where: x is the weighted sum of the input, were used for the prediction of rehydration indices RI_1, RI_2, RI_3, RI_4, WAC (Table 2).

The "trainlm" (Levenberg-Marquardt) training function and "learngdm" (gradient descent with momentum weight and bias learning function) adaptation learning function were used in this study (Fig. 4).

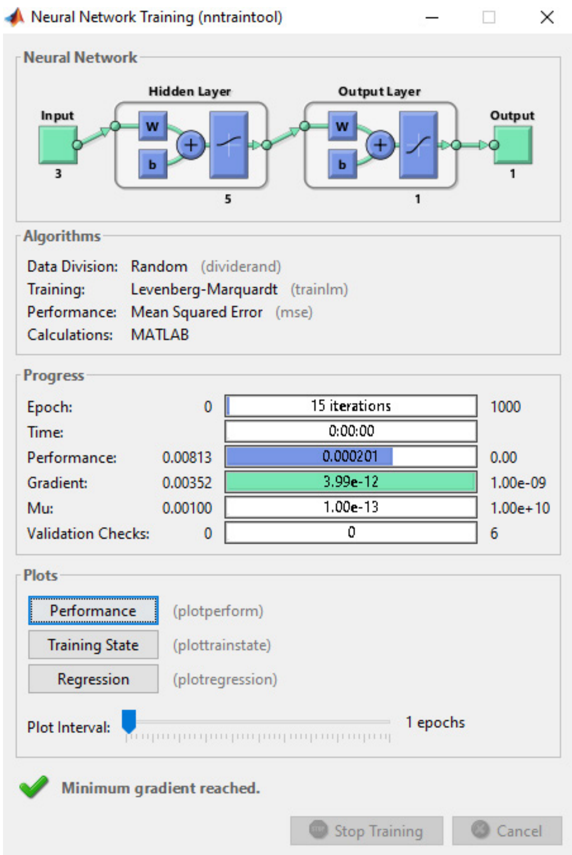

Fig. 4. Neural network training window (for RI_1).

Table 2 presents the parameters of each neural network. The highest values of the correlation coefficient were obtained for the neural networks describing rehydration indices RI_1 and RI_2 (validation: 0.988 and 0.958, respectively.

Weights: D_{1i}, D_{2i}, D_{3i} and bias D_{4i} in the transfer function for each ANN are presented in Table 3 for the algorithm with three neurons.

The neural networks presented in the work, used for the description of the rehydration indices (respective Eqs (11)-(13) and weights and biases from Table 3) are not difficult to use. These models produce good results with regard to rehydration indices calculations. The results of the statistical analysis are presented in Table 4. The obtained values of correlation coefficients R were high (the highest value for index RI_1), and were within the range of 0.9385 – 0.9608. The lowest MBE values were obtained for networks describing rehydration indices RI_1 and RI_4: 0.00019 and -0.00020, respectively. The lowest values of RMSE were obtained for neural networks describing rehydration indices RI_2 and RI_4: 0.0106 and 0.0109, respectively, while networks describing rehydration indices WAC and RI_3 had the highest values. The lowest values of χ^2 were obtained for the neural networks describing rehydration indices RI_2 and RI_4: 0.00013 and 0.00015, respectively, while the highest values were obtained for the neural networks describing rehydration indices RI_1 and RI_3: 0.00025 and 0.00060, respectively. The lowest values of t-stat were obtained for neural networks describing rehydration indices RI_1, RI_4 and RI_3, equal to 0.0647, 0.0924 and 0.1079, respectively, while the highest values were obtained for neural networks describing the rehydration indices RI_2 and WAC – 0.2337 and 0.6685, respectively. These results demonstrate that all of the ANNs, which were utilized in this research, sufficiently predicted the rehydration indices behaviour.

In the backward stepwise method, used in this study, three models (for each rehydration indices) were generated, using only two of the variables as inputs. The omitted variable for which the resulting models gave the largest error is the most important one. Table 5 presents the backward stepwise result in which three models were generated using two of the available variables. The R, MSE, RMSE, χ^2 and *t*-stat of each model is presented in Table 5.

The rehydration temperature has the greatest impact on all of the rehydration indices, with the exception of the errors of *t*-stat T_r, for which it occupied the 2nd (indices RI_4, WAC) or 3rd (index RI_3) position. The significant impact of the rehydration temperature on all of the tested rehydration indices is shown in Figs 1-3.

The drying temperature (with the exception of the MSE error) has a lower impact on the rehydration index RI_1 than T_r. The same applies to index RI_2 (with the exception of R and RMSE errors). The rehydration index RI_3 is influenced to a lesser extent by the velocity of the drying air (*t*-stat error indicates the greatest influence of v) than by T_r, while index RI_4 is influenced to a lesser extent by the drying temperature than by T_r (with the exception of MSE and *t*-state errors). T_r has the greatest influence on the WAC rehydration index (with the exception of MBE and *t*-stat errors), followed by the velocity of the drying air, and T_d , which has the lowest influence on WAC.

CONCLUSIONS

1. The present study showed that the drying temperature, drying air velocity and rehydration temperature all had an effect on the rehydration indices tested. The highest values of the rehydration indices: RI_1, RI_2, and RI_3 characterized apples dried at 70°C (v=2 m s^{-1}) and rehydrated at 70°C, whereas for the highest value of RI_4: T_d=70 °C, v=0.5 m s^{-1}, T_r=45°C, and for the highest WAC value: T_d=60 °C, v=6 m s^{-1}, T_r=70°C.

Table 3. Weights and biases between input and hidden layers and between hidden and output layers

Rehydration index	No.	Weights and biases between input and hidden layers				Weights and biases between hidden and output layers	
		Weights			Bias	Weight	Bias
	i	D_{1i}	D_{2i}	D_{3i}	D_{4i}	W_i	B_i
RI_1	1	2.2263	-5.0363	-2.674	-3.8937	2.1603	-2.4357
	2	1.4073	-2.8087	4.3445	-4.9905	-1.9542	
	3	-1.1614	1.1078	2.9658	1.6996	4.3315	
	4	8.9821	4.5336	-2.799	-0.0285	1.3050	
	5	3.1877	2.0492	2.6279	5.0453	-1.2892	
RI_2	1	0.91143	-0.27934	-0.6559	-1.2366	1.8747	0.4334
	2	-0.8299	-0.0402	2.7575	-2.0663	-0.4097	
	3	-1.4268	0.30478	5.0284	0.8122	0.6729	
	4	4.7272	3.8261	1.9944	3.7159	-0.3895	
	5	-1.6374	2.1463	3.4860	5.1930	0.7983	
RI_3	1	3.2503	-0.2115	-2.0313	-3.2770	2.6335	-1.5037
	2	-1.8275	0.0702	4.1950	-3.8481	-1.2753	
	3	-1.3689	-0.00198	9.0181	1.8186	1.4881	
	4	6.3106	6.2380	3.5614	5.6725	-1.0460	
	5	-2.1551	4.6745	5.8387	10.0079	1.2407	
RI_4	1	6.6225	-0.3203	-5.8576	-4.2217	1.1220	0.0176
	2	-4.6245	-0.4371	11.6314	-8.5315	-1.0395	
	3	-0.6546	0.9401	8.2053	2.2298	1.4923	
	4	1.5662	4.6846	-1.1206	4.5055	2.5264	
	5	3.2771	2.5519	0.1810	2.3151	-3.7055	
WAC	1	4.412	-3.6328	-3.4425	-4.5383	-2.1287	-2.2130
	2	-2.5595	1.0019	-7.4127	1.5151	-2.7469	
	3	1.1076	-4.1162	-1.7051	-2.2043	2.6620	
	4	-1.4307	1.7808	-6.7500	4.6618	4.1876	

Table 4. Comparison between the results of statistical analyses concerning the modelling of rehydration indices

Rehydration index	R	MBE	RMSE	χ^2	*t*-stat
RI_1	0.9608	0.0002	0.0144	0.0003	0.0647
RI_2	0.9515	0.0005	0.0106	0.0001	0.2337
RI_3	0.9498	0.0005	0.0227	0.0006	0.1079
RI_4	0.9385	-0.0002	0.0109	0.0002	0.0924
WAC	0.9475	-0.0018	0.0123	0.0002	0.6685

2. The proposed ANN (MLP 3-5-1 (rehydration indices: RI_1-RI_4) and MLP 3-4-1 (WAC)) accurately describe the properties of apple cubes dried at different drying process parameters (R∈(0.9385-0.9608), MBE∈(-0.0018-0.0005), RMSE∈(0.0106-0.0227), χ^2∈(0.0001-0.0006), *t*-stat∈(0.0647-0.6685)), rehydrated at different temperatures. The proposed neural networks describe the rehydration index RI_1 for T_d∈[50-70 °C], v∈[0.01-2 m s^{-1}], T_r∈[20-95°C], rehydration indices RI_2, RI_3 and RI_4 for T_d∈[50-70°C], v∈[0.01-6 m s^{-1}], T_r∈[20-95°C], and the WAC rehydration index for T_d∈[50-70°C], v∈[2-6 m s^{-1}],

Table 5. Sensitivity analysis for rehydration indices – stepwise method

Rehydration index	Omitted parameter	R	MBE	RMSE	χ^2	t-stat
	T_d	0.8371(2)*	0.00175(3)	0.02848(2)	0.00097(2)	0.30800(2)
RI_1	v	0.9462(3)	0.00091(2)	0.01690(3)	0.00034(3)	0.27045(3)
	T_r	0.5828(1)	-0.00504(1)	0.04262(1)	0.00217(1)	0.59581(1)
	T_d	0.9481(3)	-0.00018(2)	0.01061(3)	0.00013(2)	0.08477(2)
RI_2	v	0.9466(2)	0.00009(3)	0.01069(2)	0.00013(2)	0.04241(3)
	T_r	0.9330(1)	0.00028(1)	0.01175(2)	0.00016(1)	0.12092(1)
	T_d	0.8763(3)	-0.00193(3)	0.03411(3)	0.00136(3)	0.28330(2)
RI_3	v	0.8208(2)	-0.00247(2)	0.03687(2)	0.00159(2)	0.33589(1)
	T_r	0.5453(1)	-0.00308(1)	0.05692(1)	0.00378(1)	0.27114(3)
	T_d	0.7887(2)	-0.00103(3)	0.01938(2)	0.00049(2)	0.26610(3)
RI_4	v	0.9080(3)	0.00110(2)	0.01322(3)	0.00023(3)	0.41931(1)
	T_r	0.1469(1)	-0.00181(1)	0.03158(1)	0.00129(1)	0.28705(2)
	T_d	0.8184(3)	-0.00070(3)	0.02195(3)	0.00061(3)	0.14188(3)
WAC	v	0.7450(2)	-0.00233(1)	0.02593(2)	0.00085(2)	0.40428(1)
	T_r	0.4586(1)	0.00169(2)	0.03374(1)	0.00143(1)	0.22376(2)

*Parameter impact classification.

$T_r \in$[20-95°C]. A sensitivity analysis of the ANN (backward stepwise method) demonstrates that T_r has the greatest impact on all of the rehydration indices, followed by T_d (for rehydration indices RI_1, RI_2, RI_4), and v (for rehydration indices RI_3 and WAC).

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

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

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