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Empirical modelling of dry matter of solid changes during the rehydration of dried apples pretreated by different methods before drying*

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Abstract: *Empirical modelling of dry matter of solid changes during the rehydration of dried apples pretreated by different methods before drying.* Five empirical models (Peleg, Pilosof-Boquet-Batholomai, Sing and Kulshrestha, Witrowa--Rajchert and Wesołowski) were investigated for their suitability to describe dry matter of solid changes during the rehydration of dried apples pretreated before drying. Following methods of pretreatment at temperature 20°C were applied: (i) 10 min in apple juice and then 10 min under the pressure diminished by 0.02 MPa, (ii) 30 min in 61.5% sucrose solution, (iii) 120 min in 61.5% sucrose solution. Samples (slices of 10-milimeter--thickness) were dried in a convective dryer. Air velocity was kept at 2 m/s and air temperature was kept at 60°C. The dried apples samples (the initial moisture content of approx. 6%) were rehydrated by immersion in: (i) distilled water at temperatures 20, 45, 70, and 95°C, (ii) apple juice at temperature 20°C, (iii) 0.5% citric acid solution at temperature 20°C, (iv) 16.5% sucrose solution at temperature 20°C. The accuracies of the models were measured using the root mean square error (RMSE), determination coefficient (R^2), and reduced chi-square (χ^2). All models except that used by Wesołowski described the rehydration characteristics satisfactorily (RMSE = 0.022 – 0.199, R^2 = 0.808 – 0.934, χ^2 = 0.001 – 0.046). The method of pretreatment influence the values of equilibrium dry matter of solid but any trends can be observed.

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Key words: rehydration, drying, pretreatment, mathematical model, apple

INTRODUCTION

In the rehydration process, two main crosscurrent mass fluxes are involved, 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 solutions. The analysis of the rehydration kinetics can be very useful for optimizing process conditions. Different authors have modelled the rehydration process, some of them considering a diffusion controlled mechanism and analyzing the experimental data based on Fick's law of diffusion [García-Pascual et al. 2006, Falade and Abbo 2007, Górnicki 2011]. However, a relatively simple equations were proposed [Pilosof et al. 1985, Singh et al. 1987, Peleg 1988, Witrowa-Rajchert 1999, Wesołowski 2000] to fit data sorption. Although not derived from any physical laws and hence empirical, their application is relatively easy [Górnicki 2010, Kaleta et al. 2010].

The aim of this study was to discuss the suitability of chosen empirical models for describing dry matter of solid changes during the rehydration of dried apples variety Ligol pretreated by different methods before drying.

MATERIALS AND METHODS

Ligol variety apples used in this study were acquired in local market. Homogenous lots were selected according to such maturity indicators as fruit size and appearance. Large, yellow, and covered with bright red blush apples were chosen. They had cream-coloured, crispy, and juicy flesh and good aroma. Apples were cut into slices of 10-milimeter--thickness. Before drying slices were pretreated at 20°C by following methods: (i) 10 min in apple juice and then 10 min under the pressure diminished by 0.02 MPa, (ii) 30 min in 61.5% sucrose solution, (iii) 120 min in 61.5% sucrose solution. Samples were dried in a convective dryer. Air velocity was kept at 2 m/s and air temperature was kept at 60°C. Drying was continued until no further changes in mass sample were observed. Experiments were replicated three times. Dried material obtained in the same conditions was stored in airtight glass container until it was used in the rehydration experiments.

The dried apple samples (the initial moisture content of approx. 6%) were rehydrated by immersion in: (i) distilled water at 20, 45, 70, and 95°C, (ii) apple juice at 20°C, (iii) 0.5% citric acid solution at 20°C, (iv) 16.5% sucrose solution at 20°C. An initial amount of 10 g of dried apples was used in each trial. The measurements lasted from 2 h (for distilled water at 95°C) to 6 h (for each medium at 20°C). Dry matter of solid was determined according to AOAC (2003) standards. Dry matter was determined seven times during the rehydration. The electronic scales WPE-300 (RADWAG, Radom, Poland) were used for weighting of dry matter of samples with accuracy of ±0.001 g. The maximum relative error was 0.1%. The measurements were replicated three times.

The following empirical models were used to describe the rehydration kinetics:

– the Peleg [1988] model

$$\frac{m_{d.m.}(t)}{m_{d.m.0}} = 1 - \frac{t}{A_1 + A_2 t} \tag{1}$$

– the Pilosof-Boquet-Batholomai [1985] model

$$\frac{m_{d.m.}(t)}{m_{d.m.0}} = 1 + \frac{A_3 t}{A_4 + t} \tag{2}$$

– the Singh and Kulshrestha [1987] model

$$\frac{m_{d.m.}(t)}{m_{d.m.0}} = 1 - \frac{A_5 A_6 t}{A_6 t + 1} \tag{3}$$

– the Witrowa-Rajchert [1999] model

$$\frac{m_{d.m.}(t)}{m_{d.m.0}} = A - B\left(1 - \frac{1}{1 + BCt}\right) \tag{4}$$

– the Wesołowski [2000] model

$$\frac{m_{d.m.}(t)}{m_{d.m.0}} = A\left(B + \mathrm{e}^{-Ct}\right) \tag{5}$$

where:
$m_{d.m.}(t)$ – the dry matter of solid of rehydrated sample [g];
$m_{d.m.0}$ – the dry matter of solid of dried material [g];
t – the time [h];

A_1 – Peleg rate constant [h];
A_2 – Peleg capacity constant;
A, A_3, A_4, A_5, A_6, B, and C – constants.

Following statistical test methods were used to evaluate statistically the performance of the tested models: the root mean square error (RMSE), the coefficient of determination (R^2) and reduced chi-square (χ^2). The higher the value of R^2, and lower the values of RMSE and χ^2, the better the goodness of the fit. In this study, the regression analyses were done using the STATISTICA routine.

The discussed models can be used for determination of the equilibrium dry matter of solid $m_{d.m.e}$. Assuming $t \to \infty$ in Eqs. (1)–(5) one obtains: (i) $m_{d.m.e.}/m_{d.m.0} = 1 - A_2^{-1}$ for the Peleg model, (ii) $m_{d.m.e}/m_{d.m.0} = 1 + A_3$ for the Pilosof-Boquet-Batholomai model, (iii) $m_{d.m.e}/m_{d.m.0} = 1 - A_5$ for the Sing and Kulshrestha model, (iv) $m_{d.m.e}/m_{d.m.0} = A - B$ for the Witrowa-Rajchert model, and (v) $m_{d.m.e}/m_{d.m.0} = A \cdot B$ for the Wesołowski model.

RESULTS AND DISCUSSION

Example of variation in relative dry matter of solid changes [$m_{d.m.}(t)/m_{d.m.0}$] during the rehydration of apple slices (pretreated before drying at 20°C in apple juice for 10 min and then 10 min under the pressure diminished by 0.02 MPa, dried in convective dryer at 60°C and 2 m/s) immersed in distilled water at 20°C and the results of verification of the considered empirical models are presented in Figure 1a–c. It can be observed that solute loss increases with increasing rehydration time, and the rate is faster in the initial period of rehydration and decreased up to the saturation level. The explanation of such a course of variation in dry matter of solid with time can be the following. There is an initial steep decrease in solid content because of a high rate of mass transfer (solid gradient). As the solute concentration equilibrated with the environment, the rate of change of solid dry matter is substantially reduced [Sopade et al. 2007]. Similar findings have been noted in the previous studies [Witrowa-Rajchert 1999, Rastogi et al. 2004, Nayak et al. 2006, Górnicki 2011] and for the other experiments conducted in this work.

It can be observed from Figure 1a–c that five considered empirical models describe the course of rehydration curve well but all models overestimate the experimental values. Analysis of all obtained graphs shows similar values of absolute and relative errors.

The exemplary results of statistical analyses on the modelling of dry matter of solid changes during the rehydration of dried apple slices in 16.5% sucrose solution at 20°C and the summary results (for all experiments conducted in this work) of statistical analyses on the modelling of dry matter of solid changes during the rehydration of dried apple slices are given in Tables 1 and 2. It turned out from the statistical analyses that all models except that used by Wesołowski described the dehydration characteristics satisfactorily. The values of RMSE, R^2, and χ^2 are comparable for the Peleg model, the Pilosof-Boquet-Batholomai model, the Singh and Kulshrestha model, and the Witrowa-Rajchert model.

Among these four models Peleg model has been most often used. It has been verified not only for the increase of

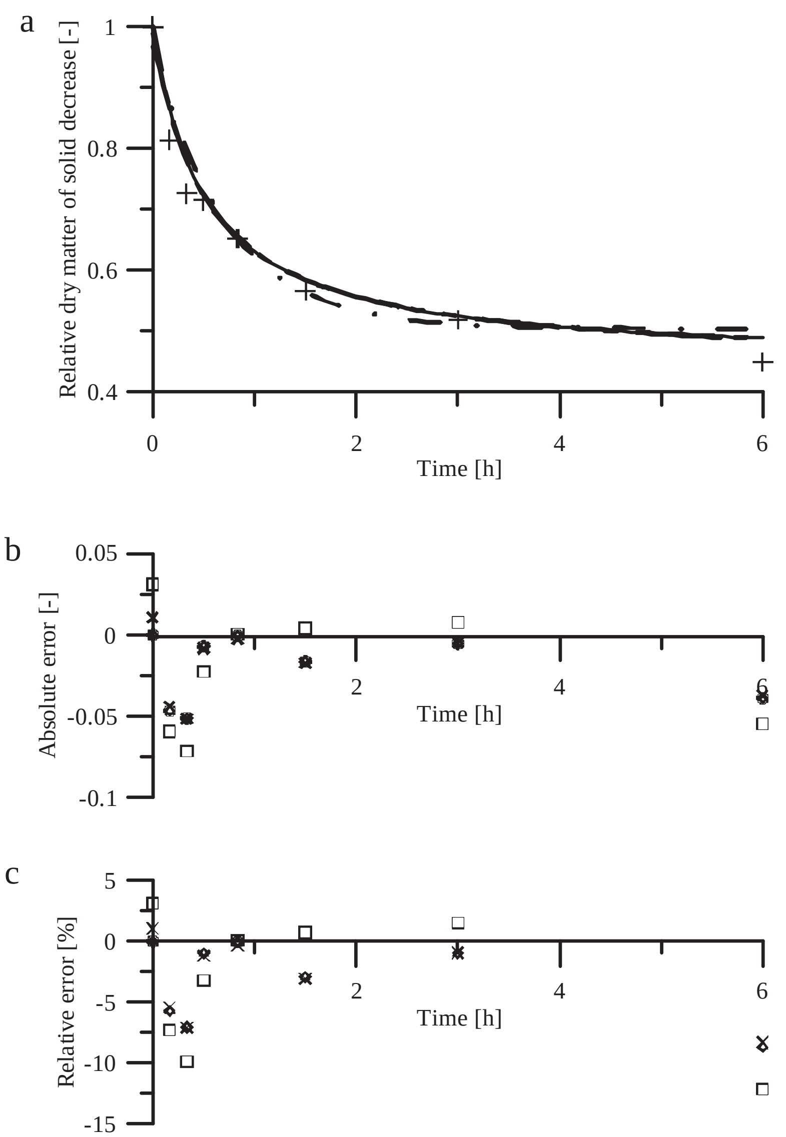

FIGURE 1. Verification of the considered empirical models for the rehydration of apple slices (pretreated before drying at 20°C in apple juice for 10 min and then 10 min under the pressure diminished by 0.02 MPa, dried in convective dryer at 60°C and 2 m/s) immersed in distiller water at 20°C: (a) relative dry matter decrease vs. time; (+) experimental data, (——) Peleg model, (- - - -) Pilosof-Boquet--Batholomai model, (– – –) Singh and Kulshrestha model, (— —) Witrowa-Rajchert model, (— · —) Wesołowski model, (b) absolute error of rehydration curve approximation; (○) Peleg model, (Δ) Pilosof-Boquet-Batholomai model, (◊) Singh and Kulshrestha model, (x) Witrowa-Rajchert model, (□) Wesołowski model, (c) relative error of rehydration curve approximation; (○) Peleg model, (Δ) Pilosof-Boquet-Batholomai model, (◊) Singh and Kulshrestha model, (x) Witrowa-Rajchert model, (□) Wesołowski model

TABLE 1. Results of statistical analyses on the modelling of dry matter of solid changes during the rehydration of dried apple slices in 16.5% sucrose solution at 20°C

Method of pretreatment	Model name	Equation	Model parameters	Equilibrium value	RMSE	R^2	χ^2
10 min in apple juice and then 10 min under the pressure diminished by 0.02 MPa at 20°C	P	1	A_1 = 1.812 A_2 = 4.942	0.80	0.022	0.904	0.001
	PBB	2	A_3 = –0.202 A_4 = 0.367	0.80	0.022	0.904	0.001
	SK	3	A_5 = 0.202 A_6 = 2.727	0.80	0.022	0.904	0.001
	W-R	4	A = 1.004 B = 0.206 C = 13.85	0.80	0.022	0.904	0.001
	W	5	A = 0.184 B = 4.445 C = 2.280	0.82	0.212	0.912	0.057
30 min in 61.5% sucrose solution at 20°C	P	1	A_1 = 0.692 A_2 = 3.839	0.74	0.037	0.844	0.002
	PBB	2	A_3 = –0.261 A_4 = 0.180	0.74	0.037	0.844	0.002
	SK	3	A_5 = 0.261 A_6 = 5.550	0.74	0.037	0.844	0.002
	W-R	4	A = 0.995 B = 0.256 C = 20.61	0.74	0.037	0.844	0.002
	W	5	A = 0.226 B = 3.350 C = 3.162	0.76	0.224	0.800	0.061
120 min in 61.5% sucrose solution at 20°C	P	1	A_1 = 0.696 A_2 = 3.463	0.71	0.038	0.871	0.002
	PBB	2	A_3 = –0.289 A_4 = 0.201	0.71	0.038	0.871	0.002
	SK	3	A_5 = 0.289 A_6 = 4.976	0.71	0.199	0.871	0.046
	W-R	4	A = 0.999 B = 0.287 C = 17.13	0.71	0.038	0.871	0.001
	W	5	A = 0.264 B = 2.752 C = 2.824	0.73	0.292	0.868	0.108

P – Peleg; PBB – Pilosof-Boquet-Batholomai; SK – Singh and Kulshrestha; W-R – Witrowa-Rajchert; W – Wesołowski.

TABLE 2. Summary results of statistical analyses on the modelling of dry matter of solid changes during the rehydration of dried apple slices

Model name	Equation	Equilibrium value	RMSE	R^2	χ^2
Peleg	1	0.439–0.798	0.022–0.194	0.808–0.934	0.001–0.043
Pilosof-Boquet--Batholomai	2	0.439–0.798	0.022–0.194	0.808–0.934	0.001–0.043
Singh and Kulshrestha	3	0.439–0.798	0.022–0.199	0.808–0.934	0.001–0.046
Witrowa-Rajchert	4	0.438–0.798	0.022–0.194	0.808–0.934	0.001–0.046
Wesołowski	5	0.506–0.819	0.212–0.545	0.732–0.917	0.056–0.361

moisture content [Masckan 2002, García--Pascual et al. 2006, Gowen et al. 2007, Moreira et al. 2008], but also for the decrease of dry matter of solid during the rehydration of such dried products as apple cv. 'Granny Smith' [Atarés et al. 2008, 2009], carrots [Markowski and Zielińska 2011], and mango [Giraldo et al. 2006]. The conditions of drying and rehydration of apples at papers mentioned earlier were different from conditions applied in this work.

Other models which describe the decrease of dry matter of solid during the rehydration of dried apples cv. 'Ligol' namely: Pilosof-Boquet-Batholomai model, Singh and Kulshrestha model, and Witrowa-Rajchert model have been used less often in comparison with Peleg model. Shittu et al. [2004] described the rehydration of dried breadfruits seeds using Pilosof-Boquet-Batholomai model and Singh and Kulshrestha model. The same models were applied by Sopade et al. [2007] for describing water absorption of wheat starch, whey protein concentrate, and whey protein isolate. The model proposed by Witrowa-Rajchert has been applied for the describing the rehydration of dried apples cv. 'Idared', carrots, potatoes, and pumpkins [Witrowa-Rajchert 1999] and dried parsleys [Kaleta and Górnicki 2006, Kaleta et al. 2008].

The values of equilibrium dry matter of solid obtained from the four mentioned above models are the same. The Wesołowski model gave higher values of equilibrium dry matter of solid. The method of pretreatment influence the discussed values but any trends can be observed.

CONCLUSIONS

Five empirical models were investigated for their suitability to describe the dry matter of solid changes during the rehydration of dried apples pretreated by different methods before drying. The root mean square error, the determination coefficient, and reduced chi-square were estimated for all models considered to compare their goodness of fit the experimental rehydration data. The following models: Peleg, Pilosof-Boquet--Batholomai, Singh and Kulshrestha, and Witrowa-Rajchert described the rehydration characteristics satisfactorily.

REFERENCES

AOAC 2003: Official methods of analysis. Association of Official Analytical Chemists No 934.06, Arlington VA.

ATÁRES L., CHIRALT A., GONZÁLEZ--MARTINEZ C. 2009: Effect of the impregnated solute on air drying and rehydration of apple slices (cv. Granny Smith). J. Food Eng. 91: 305–310.

ATÁRES L., CHIRALT A., GONZÁLEZ--MARTINEZ C. 2008: Effect of solute on osmotic dehydration and rehydration of vacuum impregnated apple cylinders (cv. Granny Smith). J. Food Eng. 89: 49–56.

FALADE K.O., ABBO E.S. 2007: Air-drying and rehydration characteristics of date palm (*Phoenix dactylifera* L.) fruits. J. Food Eng. 79: 724–730.

GARCÍA-PASCUAL P., SANJUÁN N., MELIS R., MULET A. 2006: *Morchella estulenta* (morel) rehydration process modelling. J. Food Eng. 72: 346–353.

GIRALDO G., VÁZQUEZ R., MARTÍN--ESPARZA M.E., CHIRALT A. 2006: Rehydration kinetics and soluble solids lixiviation of candied mango fruit as effected by sucrose concentration. J. Food Eng. 77: 825–834.

GÓRNICKI K. 2010: Effect of convectional drying parameters on rehydration kinetics of parsley dried slices. Annals of Warsaw University of Life Sciences – SGGW. Agriculture (Agricultural Engineering) 55: 27–33.

GÓRNICKI K. 2011: Modelowanie procesu rehydratacji wybranych warzyw i owoców. Wydawnictwo SGGW, Warszawa.

GOWEN A., ABU-GHANNAM N., FRIAS J., OLIVEIRA J. 2007: Influence of preblanching on the water absorption kinetics of soybeans. J. Food Eng. 78: 965–971.

KALETA A., GÓRNICKI K. 2006: Effect of initial processing methods used in convectional drying process on the rate of getting equilibrium state in rehydrated dried parsley root. Annals of Warsaw Agricultural University – SGGW. Agriculture (Agricultural Engineering) 49: 9–13.

KALETA A., GÓRNICKI K., GÓRNICKA M. 2008: Drying parameters of parsley roots and rehydration kinetics of dried parsley roots. [In:] B. Dobrzański jr., S. Grundas, R. Rybczyński (Eds). Physical methods of diagnostics of plant materials and food products. Wyd. Nauk. FRNA, Komitet Agrofizyki PAN, Lublin, Poland (in Polish): 87–106.

KALETA A., GÓRNICKI K., KOWALIK A., BRYŚ A. 2010. Investigations on rehydration process of dried prunes, apples and strawberries obtained under industrial conditions. Annals of Warsaw University of Life Sciences – SGGW. Agriculture (Agricultural Engineering) 55: 9–13.

MARKOWSKI M., ZIELIŃSKA M. 2011: Kinetics of water absorption and soluble--solid loss of hot-air-dried carrtos during rehydration. Int. J. Food Sci. Technol. 46: 1122–1128.

MASCAN M. 2002: Effect of processing on hydration kinetics of three wheat products of the same variety. J. Food Eng. 52: 337–341.

MOREIRA R., CHENLO F., CHAGURI L., FERNANDES C. 2008: Water absorption, texture, and color kinetics of air-dried chestnuts during rehydration. J. Food Eng. 86: 584–594.

NAYAK C.A., SUGUNA K., RASTOGI N.K. 2006: Combined effect of gamma--irradiation and osmotic treatment on mass transfer during rehydration of carrots. J. Food Eng. 74(1): 134–142.

PELEG M. 1988: An empirical model for the description of moisture sorption curves. J. Food Sci. 53: 1216–1219.

PILOSOF A.M.R., BOQUET R., BATHOLOMAI G.B. 1985: Kinetics of water uptake by food powders. J. Food Sci. 50: 278–279.

RASTOGI N.K., NAYAK C.A., RAGHAVARO K.S.M.S. 2004: Influence of osmotic pre-treatments on rehydration characteristics of carrots. J. Food Eng. 65(2): 287–292.

SHITTU T.A., AWONORIN S.O., RAJI A.O. 2004: Evaluating some empirical models for predicting water absorption in african breadfruit (*Treculia africana*) seeds. Int. J. Food Prop. 7(3): 585–602.

SINGH B.P.N., KULSHRESTHA S.P. 1987: Kinetics of water sorption by soybean and pigeonpea grains. J. Food Sci. 52: 1538–1541.

SOPADE P.A., XUN P.Y., HALLEY P.J., HARDIN M., 2007: Equivalence of the Peleg, Pilosof and Singh-Kulshrestha models for water absorption in food. J. Food Eng. 78(2): 730–734.

WESOŁOWSKI A. 2000: Badanie suszenia jabłek promieniami podczerwonymi. Rozprawa doktorska. SGGW, Warszawa.

WITROWA-RAJCHERT D. 1999: Rehydracja jako wskaźnik zmian zachodzących w tkance roślinnej podczas suszenia. Fundacja "Rozwój SGGW", Warszawa.

Streszczenie: *Empiryczne modelowanie zmian masy suchej substancji w procesie rehydratacji suszonych jabłek poddanych różnym metodom obróbki wstępnej przed suszeniem.* Badano pięć empirycznych modeli: Pelega, Pilosof-Boquet-Batholomai, Singh i Kulshrestha, Witrowej-Rajchert oraz Wesołowskiego, pod kątem ich przydatności do opisu zmian masy suchej substancji suszonych jabłek w procesie ich rehydratacji. Materiałem badawczym były 10-milimetrowe plastry jabłek suszone w warunkach konwekcji wymuszonej (w temperaturze 60°C i przy prędkości czynnika suszącego 2 m/s). Przed suszeniem krajankę jabłek poddawano następującym metodom obróbki wstępnej (w temperaturze 20°C): 10 min w soku jabłkowym, a następnie 10 min pod ciśnieniem pomniejszonym o 0,02 MPa, 30 min w 61,5-procentowym roztworze sacharozy, 120 min w 61,5-procentowym roztworze sacharozy. Proces rehydratacji prowadzono w wodzie destylowanej w 20, 45, 70 i 95°C, soku jabłkowym w 20°C, 0,5-procentowym roztworze kwasku cytrynowego w 20°C. Miarą dokładności dopasowania danych otrzymanych z modeli do danych empirycznych były: pierwiastek błędu średniokwadratowego (RMSE), współczynnik determinacji (R^2) oraz zredukowany chi-kwadrat (χ^2). Wszystkie badane empiryczne modele, oprócz modelu Wesołowskiego, można uznać za odpowiednie do opisu zmian masy suchej substancji w suszonych jabłkach w procesie ich rehydratacji (RMSE = 0,022–0,199, R^2 = 0,808–0,934, χ^2 = 0,001–0,046). Badane metody obróbki wstępnej miały wpływ na wartość równowagowej masy suchej substancji, lecz nie zaobserwowano wyraźnych tendencji.

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