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Chokeberry thin layer convective drying process modeling and energy efficiency estimation

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Abstract. The effective moisture diffusivity (D_{eff}), the energy of activation (E_a) and total energy input (Q) are appropriate parameters for modeling and energy efficiency estimation of the thin layer dehydration process of chokeberry under the different air temperature (50, 55, 60, 65 and 70 °C). Increasing the dehydration temperature will statistically significantly increased the D_{eff} from 2.93×10^{-6} m^2 s^{-1} (50 °C) to 7.77×10^{-6} m^2 s^{-1} (70 °C), and decreased the E_i from 2594.77 kJ to 2474.35 kJ, respectively. As the drying temperature was increased and consecutive drying time has been reduced (from 37 hours to 23 hours), energy input statistically significantly decreased. Mathematical models showed a good correlation between calculated and experimental values and allowed good prediction of dehydration parameters, enhancing energy efficiency. The E_a for the experimental model of thin layer chokeberry dehydration was 45.37 kJ mol^{-1}.

1. Introduction

Food drying is a complex process because of the differential structure of products, with simultaneous heat and mass transfer [1]. In practice, a food dryer and effective models of drying are necessary for dehydration design, optimization, energy efficiency estimation, and process control. The drying parameters, such as drying temperature, pressure, air velocity, relative humidity, material thickness and shape, and the product retention time, must be controlled according to product type, feed, purpose, and method [2, 3, 4].

Thin-layer drying is used to estimate the drying time for several products (such as fruit berries) and also to generalize energy efficiency. Physical and thermal properties of fruit berries (chokeberry), such as the heat and mass transfer, and moisture diffusion, are essential for the dryer design. The diffusion process in solid materials during the dehydration process is very complicated. It may involve molecular diffusion, different flows (capillary, Knudsen, hydrodynamic), or surface diffusion [1]. All these phenomena are systematized as effective moisture diffusivity.

The goal of this research was to develop a mathematical model of the chokeberry thin layer convective drying process and to calculate and estimate process energy efficiency at the different process parameters.

2. Materials and methods

2.1. The theoretical background of the dehydration process

Convective drying was conducted in the dehydrator (Colossus CSS 5330 250W, PRC) at temperatures of 50, 60, and 70 °C at atmospheric pressure, to the constant weight. Uncrushed chokeberry samples were placed in a tray of 320-mm diameter in a thin layer with a mass load of 3 kg m^{-2}, and the convective drying process was operated at an air velocity of 0,25 m s^{-1} [5]. The convective drying kinetic was based on mass losses of chokeberry [6]. The moisture ratio (MR) is defined according to Eq. (1):

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

M_t, M_o and M_e represent the moisture content achieved after convective drying time t, the initial moisture content, and the equilibrium moisture content, respectively. The value of equilibrium moisture content (M_e) usually is deficient and can be deleted from Eq. (1) without a significant change in the amount of MR.

The most widely used theoretical models are derived from Fick's second law of diffusion. The analytical solutions for berries (sphere, Eq. (1) and (2)) were given below [1]:

$$MR = A_1 \cdot \sum_{i=1}^{\alpha} \frac{1}{J_o^2} \cdot e^{-\frac{J_0^2 \cdot D_{eff}}{A_s}} \tag{2}$$

$$A_1 = \frac{6}{\pi^2}; \quad A_2 = 4 \cdot r^2 \tag{3}$$

where, D_{eff} is the effective moisture diffusivity (m^2 s^{-1}), t is time (s), MR is the moisture ratio, J_0 is the roots of the Bessel function, A_1, A_2 are geometric constants, and r is the radius of the sphere.

Eq. 1 is derived for the constant values of D_{eff}, and for sufficiently long drying time:

$$ln(MR) = ln(a) - k \cdot t \tag{4}$$

$$k = - \frac{\pi^2 \cdot D_{eff}}{A_2} \tag{5}$$

The variation of $ln(MR)$ versus t is linear (Eq. (4)), and the slope is equal to drying constant (k) and the constant effective moisture diffusivity can be easily calculated (Eq. (5)).

The energy of activation (E_a) was calculated using an Arrhenius type equation (Eq. (6)) [7]:

$$D_{eff} = D_0 \cdot e^{-\frac{E_a}{R \cdot T}} \tag{6}$$

where E_a is the energy of activation (kJ mol^{-1}), R is the universal gas constant (8.3143 J mol^{-1} K^{-1}), T is absolute air temperature (K), and D_0 is the pre-exponential factor of the Arrhenius equation (m^2 s^{-1}). The activation energy was calculated from the slope of the Arrhenius plot $ln(De)$ versus $1/T$, given by Eq. (7):

$$n = -\frac{E_a}{R} \tag{7}$$

2.2. Energy input calculation

Energy input (Q) during chokeberry drying was calculated via a simple experiment where the mass of distilled water was poured in a full vessel, and its temperature was measured. Then vessel with water was placed in a preheated convective dryer at defined temperatures by the experimental plan. After 10 minutes, water loss, expressed in weight, is measured. Quantity of heat needed for increase of the temperature of water samples and evaporation of determined mass of water is calculated from the following equation [8]:

$$Q = c_p \cdot m_s \cdot (T_2 - T_1) + L \cdot m_i \tag{8}$$

where are:

Q – a quantity of heat needed for heating and evaporation of determined mass of water, (kJ)

c_p – specific heat capacity of the water, (kJ kg^{-1}°C)
m_s – sample mass, (kg)
T_2 – final sample temperature, (°C)
T_1 – start sample temperature, (°C)
L – latent heat of water evaporation, (kJ kg^{-1})
m_i – a mass of evaporated water from the sample, (kg).

The calculated quantity of heat for 10 minutes was extrapolated to experimentally measured drying time of chokeberry until a constant mass was achieved.

2.3. Mathematical models calculation

Based on experimental data of drying time and coefficient of diffusion, mathematical models of the dependence of drying time and coefficient of diffusion from drying temperature, as an independent variable, are formed:

$$Y_k = f_k(\textit{drying temperature}) \quad (9)$$

The second-order polynomial is used for the approximation of experimental data. Models of 3 responses (drying time, coefficient of diffusion, and energy input) in dependence of 1 independent variable (drying temperature) are developed:

$$Y_k = a_{k0} + a_{k1} \cdot X + a_{k2} \cdot X^2 \quad k = 1\text{–}3; \quad (10)$$

where are:
$a_{k0\text{-}2}$ – regression coefficients;
Y – drying time (Y_1), coefficient of diffusion (Y_2), energy input (Y_3)
X – drying temperature.

The significance of the effect and interaction of individual factors, for every response, was determined by analysis of variance (ANOVA) and application of post-hoc Tukey HSD test. For ANOVA calculation, StatSoft Statistica ver.12.0. The software package was used, and for and second-order polynomial models' calculation Microsoft Excel ver. 2016 was used.

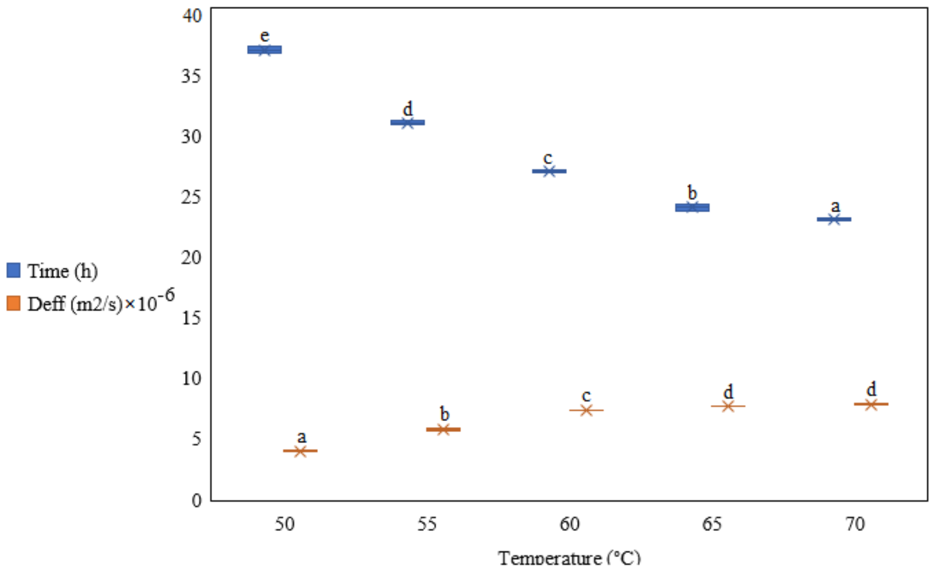
3. Results and Discussion

D_{eff} mainly varies with the product's temperature, the moisture content, air velocity, and the structure. It is in accordance with the thin layer assumption [9, 10]. Chokeberries were relatively homogeneous spheres with a diameter of 5.38±0.25 mm.

The values of drying times and the coefficient of diffusion at different drying temperatures are shown in Figure 1.

From the presented results, it can be seen that with the increase of drying temperature, a statistically significant decrease of drying duration occurred, until the constant mass of dried chokeberry is obtained. The longest drying duration was 37 hours, at the lowest drying temperature (50 °C), while the shortest drying duration of 23 hours was achieved at the highest drying temperature of 70 °C. The values of the coefficient of diffusion statistically significantly increased with the increase in drying temperature. These results are in a correlation to Mirzae et *al.* (2009) and Aghbashlo et *al.* (2008). It can be seen that there was no statistically significant difference between the coefficient of diffusion values at the two highest drying temperatures, which indicate reaching maximal values of the coefficient of diffusion at these temperatures. Minimal value of coefficient of diffusion was 2.93×10^{-6} m^2 s^{-1} ($ln(MR) = -0.0997 \cdot t + 0.1709$, R^2=0.9868), at drying temperature of 50 °C, while maximal value of 7.77×10^{-6} m^2 s^{-1}, was at drying temperature of 70 °C ($ln(MR) = -0.2647 \cdot t + 0.5641$, R^2=0.9587). Increasing the dehydration time, the slope (k) was increased too.

The activation energy (E_a) was related to the minimum amount of energy that needs to be provided to initial moisture diffusion through the chokeberries and was about n = 45.37 kJ mol^{-1}. E_a varies depending on the drying parameters and ranges from 29.35–33.78 kJ mol^{-1} for apricot to 110.837–130.61 for kJ mol^{-1} particular types of berries [2, 12].



[a-d] Different letters in superscript between marked values of the same color, indicates on statistically significant difference, at the level of significance of $p<0.05$ (based on post-hoc Tukey HSD test)

Figure 1. Average values and standard deviations of drying time and coefficient of diffusion at different drying temperatures

In Table 1, values of Q during chokeberry drying at different drying times and temperatures are shown. From the presented result, it can be seen that with the drying temperature increase and consecutive drying time decrease, energy input statistically significantly decreased. The highest value of energy input was achieved at drying temperature and time of 50 °C and 37 h. In comparison, the lowest energy input was made at drying temperature and time 70 °C and 23 h, indicating that a more energy-efficient process was at the highest temperature.

Table 1. Average values and standard deviations of energy input during chokeberry drying at different drying time and temperature

T (°C)	t (h)	Q (kJ)
50	37	2594.77 ± 11.15^{b}
55	31	2578.28 ± 9.71^{bc}
60	27	2560.10 ± 12.34^{b}
65	24	2489.46 ± 14.06^{a}
70	23	2474.35 ± 15.74^{a}

[a-c] Different letters in superscript in the Table 1 indicate on the statistically significant difference between values, at a significance level of $p<0.05$

Mathematical modeling of the thin layer dehydration of fruits usually requires the statistical methods of regression and correlation analysis. Table 2 shows regression coefficients and coefficients of correlation of developed mathematical models of drying time and coefficient of diffusion from drying temperature in chokeberry convective drying process, in the form of second-order polynomial Eq. (3). Based on second-order polynomial Eq. (3) regression coefficients ($a_0 - a_2$), mathematical models, of drying time, and the coefficient of diffusion dependence from drying temperature in the chokeberry convective drying process can be formed. High R^2 values indicate the high correspondence of calculated values with experimental data [13].

Table 2. Mathematical models of drying time and coefficient of diffusion dependence from drying temperature in chokeberry convective drying process

		t	D_{eff}	Q
Regression coefficients	a_0	181.97	-74.358	2430.9
	a_1	-4.4714	2.4876	10.444
	a_2	0.0314	-0.0188	-0.142
R^2		0.999	0.993	0.941

4. Conclusions

From the presented results, it can be concluded that:

- By increasing temperature in the process of chokeberry drying, the duration of the process can be significantly shortened, reaching maximal values of the coefficient of diffusion
- The experimental results showed that at a high air temperature (70 °C), the air had better contact with the chokeberry surface, which results in more excellent absorption of moisture. The moisture gradient was increased, which was leading to an increase in the moisture diffusivity
- Developed mathematical models of drying time and coefficient of diffusion dependence from drying temperature in chokeberry convective drying process showed a good correlation between calculated and experimental values and allowed the right prediction of process parameters
- With increasing process temperature, energy input decreased, enhancing energy efficiency.

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References

[1] Erbay Z and Icier F 2010 *Crit. Rev. Food Sci. Nutr*. **50** 441-464
[2] Mirzae E, Rafiee S, Keyhani A and Emam-Djomeh Z 2009 *Res. Agr. Ang*. **55** 114-120
[3] Anawe PA L and Adewale FJ 2018 Data on exergy and exergy analyses of drying process of onion in a batch dryer. *Data Brief*. **21** 1784
[4] Argo BD and Ubaidillah U 2020 *J. Mech. Sci. Technol.* **34** 435-442
[5] Petković M, Đurović I, Miletić N and Radovanović J 2019 *Period. Polytech. Chem. Eng.* **63** 600
[6] Szychowski PJ, Lech K, Sendra-Nadal E, Hernández F, Figiel A, Wojdyło A and Carbonell-Barrachina ÁA 2018 *Food Bioprocess Tech.* **255** 157-164
[7] Lopez A, Iguaz A, Esnoz A and Virseda P 2000 *Dry. Technol.* **18** 995-1006
[8] Toledo RT 2007 *Fundamentals of Food Process Engineering* (University of Georgia, Athens, Georgia, USA)
[9] Ece MC and Cihan A 1993 *T. Asabe.* **36** 837-840
[10] Akpinar E, Midilli A and Bicer Y 2003 *Energ. Convers. Manage.* **44** 1689-1705
[11] Aghbashlo M, Kianmehr MH and Samimi-Akhijahani H 2008 *Energ. Convers. Manage.* **49** 2865
[12] Garau MC, Simal S, Femenia A and Rossello C 2006 *J. Food Eng.* **75** 288
[13] Arsenović M, Pezo L, Stanković S, Radojević Z 2015 *Appl. Clay Sci.* **115** 108-114