DOI: 10.46793/SBT28.451P

ENERGY USAGE AND RASPBERRY CONVECTIVE AND MICROWAVE DRYING PARAMETERS

Valerija Pantelić[1], Nemanja Miletić[1], Vesna Milovanović[1], Igor Đurović[1], Marko Petković[1], Alexander Lukyanov[2], Vladimir Filipović[3]

Abstract: The drying experiments of microwave (MD) and convective (CD) dehydration of raspberries show a shorter drying time by 86–96 % and lower energy usage resulting in energy saving of 81–89 % for MD. The average drying ratio of raspberries increases by 3.5–19 times with the application of MD. Newton's, Modified Henderson, and Pabis's, Logarithmic models were successfully used to describe the drying kinetics of raspberries. Willamette and Tulameen varieties, dehydrated on 240 W MD, showed the shortest dehydration time, the minimum energy usage, and the most efficient diffusion.

Keywords: drying, convection, microwave, raspberry, energy.

Introduction

Raspberries are considered to be a very perishable commodity because their moisture content is higher than 80%. Drying is a suitable modification of post-harvest management (Misha et al., 2022).

Microwave drying is a fourth-generation, drying technology. The key benefit of microwave drying, compared to convective drying, is its ability to preserve the quality and nutrients of the dried product. This is because the microwave energy heats the product from the inside out, leading to a more uniform drying process and reduced exposure to high temperatures that can cause oxidation and nutrient loss (Bórquez et al., 2010). Microwave energy can penetrate deep into the product and quickly remove moisture, leading to faster drying times and improved efficiency (Rodriguez et al., 2017).

The objective is to find the drying model that uses the lowest energy during raspberry drying and to determine the behavior and parameters of the model that can be used to optimize the drying process.

[1]University of Kragujevac, Faculty of Agronomy, Cara Dušana 34, Čačak, Serbia (p.valeria.19@gmail.com)

[2]Don State Technical University, Ploshchad' Gagarina 1, Rostov-on-Don, Rostov Oblast, Russia

[3]University of Novi Sad, Faculty of Technology, Cara Lazara 1, Novi Sad, Serbia

Materials and methods

Raspberry varieties the Willamette and Tulameen were grown under organic agricultural conditions, on a family farm (village Gornji Dubac 43°39′54″N, 20°21′56″E). Before the drying process, the raspberries were cleaned and washed and visually selected according to maturity level, size, and color, without mechanical damage.

Convective drying (CD) of raspberries was carried out in a dehydrator (Gorenje FDK500GCW, 380 W, air velocity of 7.9 m s^{-1}) at temperatures of 50 °C, and 70 °C at atmospheric pressure, to the constant weight (Petković et al., 2020). The microwave oven (Tesla MW2390MB 1250 W) was used for microwave drying (MD) at 90 W, and 240 W. The uncrushed raspberries were dehydrated in a thin layer with a mass load of 1.33 kg m^{-2} (100 g per tray). The moisture ratio (MR) is determined according to Eq. 1:

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

M_t, M_o, and M_e are the moisture content for drying time t, the initial moisture content, and the equilibrium moisture content, respectively. M_e is usually a deficient parameter. The drying ratio (DR) is the total mass loss of dehydrated materials ($M_{i-1} - M_i$) between two consecutive measurements ($t_{i-1} - t_i$) on a defined tray (Eq. 2):

$$DR = \frac{M_{i-1} - M_i}{t_{i-1} - t_i} \quad (2)$$

Based on the shape of the fruit (sphere), the effective moisture diffusivity D_{eff} can be calculated by Eq. 3 and Fick's second law of diffusion (Petković et al., 2021):

$$MR = \frac{6}{\pi^2} \times \sum_{i=1}^{\infty} \frac{1}{J_0^2} \times e^{-\frac{J_0^2 \times D_{eff}}{4 \times r^2}} \quad (3)$$

D_{eff} is the effective moisture diffusivity (m^2 s^{-1}), t is time (s), J_0 is the roots of the Bessel function, and r is the radius of the sphere. If the D_{eff} was constant in a relatively long drying period, Eq. 3 could be derived in ln(MR) = ln(a) – k × t. The relationship between ln(MR) and t is linear, and the slope is equal to the drying constant (k, Eq. 4):

$$k = -\frac{\pi^2 \times D_{eff}}{4 \times r^2} \quad (4)$$

An Arrhenius equation, Eq. 5 for CD, and Eq. 6 for MD, describes this effect over the energy of activation (E_a; Filipović et al., 2022):

$$D_{eff} = D_0 \times e^{-\frac{E_a}{R \times T}} \quad (5)$$

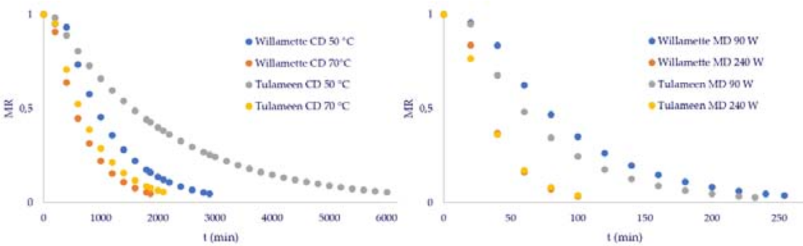
$$D_{eff} = D_0 \times e^{-\frac{E_a \times m}{P}} \quad (6)$$

where E_a (kJ mol^{-1}) is the activation energy, R (8.3143 J mol^{-1}K^{-1}) is the universal gas constant, T (K) is the absolute air temperature, and D_0 (m^2 s^{-1}) is the pre-exponential factor of the Arrhenius equation. The Eq. 5 could be simplified in $\ln(D_{eff}) = \ln(D_0) - k \times (T + 273.15)^{-1}$. The relationship between $\ln(D_{eff})$ and T is linear, and the slope is equal to the drying constant $k = E_a \times R^{-1}$. The natural logarithm of D_{eff} versus mass load m (g) versus power P (W) was used to calculate the E_a (W g^{-1}) of MD, $\ln(D_{eff}) = \ln(D_0) - k \times m\, P^{-1}$. The plot is a straight line, and the slope is equal to the drying constant $k = E_a \times R^{-1}$ (Petković et al., 2022).

Energy usage (E) for CD and MD was measured by Prosto PM 001. The mathematical relationship between energy use and carbon dioxide emissions is 1 kWh = 0.998 kg CO_2.

Results and discussion

The initial dry matter content of the Willamette and the Tulameen raspberries was 13.18±0.19 % and 15.29±0.98 % (AOAC, 1995), respectively. The rate of diffusion through a material is proportional to the concentration gradient. The rate of diffusion is influenced by factors such as the size and shape/geometry of fruits, or the temperature or input power for drying (Bórquez et al., 2010). The fastest water removal occurred in the first (initial) stage of drying, regardless of CD or MD (Graph 1).



Graph 1. MR curves of CD and MD

With an increasing temperature of CD and the power of MR, the MR curves are steeper, so the drying process was reduced. At lower CD temperatures (50 °C) and lower MD power (90 W), the MR curves are steeper and the Willamette variety drying time was shorter. At higher temperatures (70 °C) and higher power (240 W), the drying time of the Tulameen was shorter. Due to a much-reduced drying rate in the second stage, the rate of water loss was slower (the MR curve was less steep). The shortest dehydration time had the Willamette on 240 W MW (88 minutes), and the longest dehydration time had the Tulameen at

50 °C CD (6010 minutes). With the increase in temperature and power, DR was grown, as well as the fact that it was greater at the Willamette variety. MD made the DR much higher, so the largest DR (1.933 g min^{-1}, obtained at 42^{nd} minutes, Table 1) was noticed at the Willamette MD on 240 W, and the smallest DR (0.100 g min^{-1}, obtained at 173^{rd} minutes) at the Tulameen at 50 °C CD. *Szadzińska* (2018) showed the drying ratio of CD (on 55 °C) was 0.04 g min^{-1} and 0.2 g min^{-1} (MD, 100 W). The MD assistance in the drying process could shorten drying time by 94 % (Mierzwa et al., 2019). With an increasing temperature of a CD and the power of MR, D_{eff} was increased. MD of the Tulameen on 240 W had the highest resistance to mass transfer (the maximum $D_{eff} = 1.17 \times 10^{-7}$ $m^2 s^{-1}$) and was about 25 times higher than the maximum D_{eff} of CD (4.43×10^{-9} $m^2 s^{-1}$, CD of the Tulameen on 70 °C; Table 1).

Table 1. Drying parameters and energy usage/CO_2 emission of CD and MD

	DR (g min^{-1})		D_{eff} ($m^2 s^{-1}$)		E (kWh)		CO_2 (kg)	
	Willam.	Tulam.	Willam.	Tulam.	Willam.	Tulam.	Willam.	Tulam.
50 °C	0.100	0.067	3.75×10^{-10}	1.22×10^{-9}	6.215	6.533	6.203	6.520
70 °C	0.200	0.092	2.33×10^{-9}	4.43×10^{-9}	3.667	4.137	3.660	4.129
90 W	0.700	0.850	2.82×10^{-8}	4.40×10^{-8}	0.636	0.698	0.697	0.635
240 W	1.933	1.200	7.95×10^{-8}	1.17×10^{-7}	0.542	0.610	0.540	0.608

The fruit variety also affects the D_{eff} values and the drying parameters, as shown in our research. The D_{eff} ranged from 7.12×10^{-9} (CD, 65 °C) to 1.79×10^{-8} $m^2 s^{-1}$ (MD, 450 W; Abbaspour-Gilandeh et al., 2020). The E_a shows the sensibility (the necessary energy required to begin the water diffusion) of the diffusivity against temperature and power range; the greater E_a means more sensibility of D_{eff} to temperature and power. Ea, for the CD, was calculated to be 69.38 kJ mol^{-1}, while for MW was 11.74 W g^{-1} (65.22 kJ mol^{-1}, the conversion factor between W g^{-1} and kJ mol^{-1} is: 1 W g^{-1} × M (1 g mol^{-1}) × (1 kJ $(1000 J)^{-1}$). Therefore, when CD and MD are compared, lower activation energy results in more effective moisture diffusivity (higher coefficient of mass transfer) and an increase in moisture diffusion with sphere diameter (the Tulameen's radius 25.0 mm, the Willamette's radius 21.6 mm), which results in a lower energy requirement. The E, as well as the emission of CO_2, was associated with the drying model and its kinetic parameters and variety, as well. The shortest drying time will have MD models with the highest power (240 W), as well as the highest D_{eff}, which was affected by the smallest E in the drying process 0.542–0.610

kWh (Table 1, the lowest emission of CO_2). The MD reduced energy consumption by 50 % (strawberry, Szadzińska et al., 2018).

CD and MD kinetic can be determined by fitting the MR values as a function of drying time to a mathematical model (Szadzińska et al., 2018). Several mathematical models could be used to describe the drying, including Newton's, Modified Henderson and Pabis's, Logarithmic model, etc. (Mierzwa et al., 2019; Table 2). All mathematical models for MR were found to be appropriate models for the thin-layer CD and MD of raspberries, according to the high values of the coefficient of determination (> 0.900). It could be noticed, regardless of the CD and MD, the increase in the coefficients in the exponent functions (k, g, h) with the increase in T and energy, i. e. the slope was shifted toward lower values of the moisture ratio and drying time. Other parameters (a, b, c) vary slightly within the limits. Also, under the same drying conditions, the coefficients of the mathematical models have lower values for the Tulameen compared to the Willamette variety.

Table 2. Values of the coefficients for mathematical models of CD and MD

Model	Newton $MR = e^{-k\,t}$	Modified Henderson and Pabis $MR = a\,e^{-k\,t} + b\,e^{-g\,t} + c\,e^{-h\,t}$						Logarithmic $MR = a\,e^{-k\,t} + c$		
	k	a	k	b	g	c	h	a	k	c
	Willamette									
50 °C	0.0007	0.3663	0.0007	0.3666	0.00076	0.3661	0.0007	2.0679	0.0003	1.02834
70 °C	0.0012	0.3586	0.0013	0.3589	0.00132	0.3582	0.0013	1.4163	0.0007	0.3966
90 W	0.0102	0.3809	0.0113	0.3703	0.01131	0.3703	0.0113	0.6791	0.0007	0.3209
240 W	0.0189	0.3986	0.0225	0.3986	0.02255	0.3986	0.0225	2.3650	0.0067	– 1.2462
	Tulameen									
50 °C	0.0006	0.3327	0.0004	0.3386	0.00043	0.3408	0.0004	0.6911	0,0002	0.3088
70 °C	0.0011	0.3548	0.0012	0.3553	0.0012	0.3549	0.0012	1.3075	0.0007	0.2833
90 W	0.0129	0.2231	0.0169	0.4727	0.0169	0.6335	0.0169	0.6525	0,0007	0.2709
240 W	0.0207	0.3539	0.0220	0.3541	0.0220	0.3527	0.0220	2.3487	0.0062	– 1.3357

Conclusion

The use of a microwave for drying raspberries is a more efficient method compared to conventional convective drying. The shorter drying time and lower energy usage in microwave drying result in significant energy savings. Furthermore, the results suggest that the microwave drying process leads to a higher drying ratio, meaning more water is removed from the raspberries during the drying process. The use of mathematical models such as Newton's, Modified

Henderson, and Pabis's Logarithmic models to describe the drying kinetics of raspberries shows that the drying process can be accurately predicted and modeled. The study also suggests that the Willamette and Tulameen varieties of raspberries showed the best results when dried using a 240 W microwave, in terms of shortest dehydration time, minimum energy usage, and most efficient diffusion.

References

Abbaspour-Gilandeh, Y., Kaveh, M., Aziz, M. (2020). Ultrasonic-Microwave and Infrared Assisted Convective Drying of Carrot: Drying Kinetic, Quality and Energy Consumption. Applied Sciences, 10 (18), 6309.

AOAC (1995). No 934.01, 16th ed. Arlington, VA.

Bórquez, R. M., Canales, E. R., Redon, J. P. (2010). Osmotic dehydration of raspberries with vacuum pretreatment followed by microwave-vacuum drying. Journal of Food Engineering, 99 (2), 121–127.

Filipović, V., Filipović, J., Petković, M., Filipović, I., Miletić, N., Đurović, I., Lukyanov, A. (2022): Modeling convective thin-layer drying of carrot slices and quality parameters. Thermal Science, 26 (3), 2187–2198.

Mishra, S., Parth, K., Balavignesh, V., Sharma, A., Kumar, N., Narinder Kaur, E.R. (2022). A study on the dehydration of fruits using novel drying techniques. The Pharma Innovation Journal, 11 (1), 1071-1080.

Mierzwa, D., Szadzińska, J., Pawłowski, A., Pashminehazar, R., Kharaghani, A. (2019). Nonstationary convective drying of raspberries, assisted by microwaves and ultrasound. Drying Technology, 1–14.

Petković, M., Đurović, I., Miletić, N., Lukynov, A., Klyuchka, E., Radovanović, J., Donskoy, D. Y. (2020). Model of convective drying of black chokeberry (Aronia melanocarpa L.). Published in *XXV Symposium of Biotechnology*, Milošević T. (ed.), 563–569, Faculty of Agronomy Čačak, Country: Serbia.

Petković, M., Miletić, N., Kurćubić, V., Lukyanov, A., Đurović, I., Filipović, V., Mladenović, V. (2022). Energy consumption and dehydration parameters of microwave drying of carrot. Acta Agriculturae Serbica, 27 (54), 137–142.

Rodriguez, A., Rodriguez, M.M., Lemoine, M.L., Mascheroni, R.H. (2017). Study and Comparison of Different Drying Processes for Dehydration of Raspberries. Drying Technology, 35 (6), 689–698.

Szadzińska, J., Łechtańska, J., Pashminehazar, R., Kharaghani, A., Tsotsas, E. (2018). Microwave- and ultrasound-assisted convective drying of raspberries: Drying kinetics and microstructural changes. Drying Technology, 1–12.