Convective and Microwaves Dehydration Kinetics of Blackberry Fruit
(Ribes nigrum L.)

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Abstract. This work present the principal results of convective, microwave, and combined
convective-microwave dehydration of blackcurrants (Ribes nigrum) grown and harvested (2009) in the
geographic area Caraș-Severin (western Romania).

Keywords: black currant, blackberry, convective dehydration, microwaves, dehydration

INTRODUCTION

Blackcurrant (lat. Ribes nigrum) is a shrub, sporadically grown or present in the
spontaneous flora of Romania. Highly ramified, it possesses well-defined curative and
pharmaceutical properties (hypotensive, diuretic, antianemic, in the prophylaxis of chronic
degenerative rheumatism, renal conditions, etc.). The berries contain an impressive arsenal of
minerals (Mn, Mg, Fe), vitamins (C, P, PP, B1, B2, and B6), and anthocyanins. Remarkably,
vitamin C shows high stability to temperature, oxidation, etc., due to the anthocyanins that do
not block the enzyme ascorbic oxidase in the bioprocess of converting ascorbic acid into
dehydroascorbic acid. Through the significant intensification of the black hue 2-3 days
postharvest due to the content of anthocyanins and flavonoids, the thermal stability becomes
even more pronounced (Dr. Duke's Phytochemical and Ethnobotanical Databases). It contains
78.5-87.7% water, sugars (4.1-8.8%), acids (malic, citric, tartaric) (0.26-0.51%),
proteinaceous compounds (0.94-1.74%), cellulose (1.43-4.57%), minerals (0.3-0.8%).

After 3-4 days postharvest, in the absence of proper preservation (refrigeration, low
relative humidity), they degrade acceleratedly with the loss of their benefits for the
consumer’s health. Mild dehydration represents a method for the long preservation of the
bioactive mineral components transferred through the trophic chain.

Preservation by dehydration is based on the biological principle of anabiosis
(physioanabiosis), and the preservation process is that of xeroanabiosis, namely by the partial
(dehydration) or almost integral (drying) elimination of water, which means the decrease of
water activity (aw) down to the level at which the development of microorganisms is inhibited
and their enzymatic processes are blocked (aw < 0.8). If the water activity reaches the value of
0.3, the nutritional matrix can be preserved (in the absence of air) even at ambient
temperature.

From a strictly economic point of view, although the dehydration process in itself is
costly, still, by the significant reduction of the initial product’s mass, its volume, considerable
savings are made from the conditioning (packing), storage, and transport of blackcurrants.
Microwave heating is characterized by a transfer:
✓ direct of the radiations energy to the components in the fruit;
✓ rapidly localized in the product’s mass;
✓ homogeneous and fast (several minutes), without an excessive stress on the fruit surface.

The absorption of microwaves by blackcurrants manifests itself by the conversion of their energy into heat, mainly by ionic conduction and dipole rotation.

The dehydration of blackcurrants (*Ribes nigrum*) has been reported sporadically in the literature [1, 3]. The present work contributes with new experimental data from a defined geographic area in which the mineral transfer in the soil-plant-consumer trophic chain is also monitored.

**MATERIALS AND METHODS**

*Materials*

✓ blackcurrants (*Ribes nigrum* L) 2009 harvest from the geographic zones shown below (Fig. 1);
✓ dehydrating, air-dehumidifying agents.

Fig. 1. Blackcurrants (*Ribes nigrum*) and the location of the geographic areas of cultivation

The geographic area has cultivable area of sand, gravel, loess, and recent deposits, respectively. The climate is hilly moderate with oceanic and sub-Mediterranean influences, annual average temperature 7-12°C, precipitations (average value) between 600-700 mm, with predominantly westerly winds. All these factors, together with the hydrographic network, contribute to the quality of the nutritional factors in the blackcurrants grown traditionally in familial households as area-specific products.

*Equipment*

Own setup designed and structured within the department of Food Technologies of the faculty (Fig. 2).
Methods

The dehydration tests were conducted on blackcurrants 2009 harvest, previously selectively evaluated compositionally (80.28% water; 4.92% glucose; 0.37% malic acid; 0.47% minerals, the difference being made up of other nutritional principles).

The freshly harvested berries were washed, subsequently removing carefully the water droplets adhered to their surface. Simultaneously the retained peduncles and leaves were eliminated, and then it was proceeded to the dimensional calibration and sorting of mechanically and physiologically damaged blackcurrants. The vegetal matter (200 g) was laid uniformly, in a single layer, on the perforated plate (9) of the unit, having the initial and final moisture content of 80.29% (oven 105°C until constant mass) and 24.25%, respectively.

The equilibrium water content (13.58±0.2)% was estimated using the equation [4,5]:

\[
\text{Wech} = 12,144 - 0.425 \varphi + 0.015t + 0.014 \varphi^2 - 0.003 \varphi \cdot t
\]

The contact surface area of the blackcurrant mass accessed in the determinations with the flow of dry thermal agent was estimated with the relation [4]: \( A = N \cdot \pi \cdot d_{ech} \) [where \( N = \) number of blackcurrants calibrated in a determination, \( d_{ech} = \) equivalent diameter of an individual berry (m)].

After drawing the curves for dehydration \([u = f(t)]\) and the dehydration rate \( \frac{d_u}{d_t} = f(u) \) [4] from the recorded experimental data, the dehydration rate constant \((K_t)\) from the first period was also estimated \( K_t = \frac{d_u / d_t}{A \cdot (x_s - x_i)} \).

RESULTS AND DISCUSSION

In this work the main aspects (curve and rate) of dehydration of blackcurrants in convective, microwave, (high-frequency electric fields), and combined variants were investigated.

The previously prepared berries were subjected to convective dehydration in monolayers. Hot air was passed as thermal agent with a speed of 0.17 m/s.
From the analysis of blackcurrants dehydration curves \( u = f(\tau) \), in the convective variant, in an increasing series of temperatures of 60, 70, 80, 90, and 100°C, it is observed that the duration of the process depends largely on the temperature of the thermal agent.

At 60°C the operation unfolds from the initial water content of 540% to the final value of 22%, over a period of 1360 min, but at 70°C, 80°C, 90°C, and 100°C the process unfolds correspondingly in the decreasing series of water content of 1070, 920, 638, and 380. Hence it ensues that the process’s duration decreases with the increase of thermal agent’s temperature by about 4.1 times.

The analysis of dehydration rate curves demonstrates that at the utilization of the convective heat input the classical practical and theoretical considerations regarding the mass transfer mechanism in dehydration processes are verified. Two intervals are observed: the interval of constant rate and the interval of variable dehydration rate. The interval of constant rate represents about 27% of the total duration of the process, while the interval of rate decrease 70%. During the same interval the amount of evaporated water represents 47% of the total water content, and 53% in the second. This demonstrates that bound moisture in blackcurrants is 13% higher than free moisture.

The increase of thermal agent’s temperature is accompanied by the increase of the maximum dehydration rate. Thus, at 60°C it is 0.011%, at 100°C 0.0620%, a 5.7-times increase.

The shape of the dehydration rate curves, decreasing for various temperatures of the thermal agent, differs insignificantly.

On all the registers dehydration rate curves an inflexion point is observed, which coincides with the second critical point \( u_{cr2} \). At 60, 70, 80, 90, and 100°C the water content is 270, 270, 275, 250, and 200%, respectively. The critical point is the cause for the division of the interval of decreasing dehydration rate in two sections. In the first section the convexity of the dehydration rate curves is oriented toward the abscissa, and toward the ordinate in the second.

The shape of the dehydration rate curves depends largely on the internal structure of the blackcurrant fruit. Usually, for materials with similar structure, the interaction of water with the material remains the same, which justifies the similitude of the dehydration rate curves.

It is observed that the temperature of the dehydration agent influences the kinetic characteristics of the process after an exponential curve. For the same modification of the temperature the coefficient of the dehydration rate \( K_I \) increased 3.2 times in the first interval, and \( K_{II} \) 4.7 times in the second (the increase of temperature influences more the second dehydration interval).

It is known that the mass and heat transfer in the dehydration of fruit by the convective method is determined by the action of the two gradients (temperature and water content). The opposed orientation of the water content and temperature gradients is a drawback of convective dehydration, since the thermal conductivity of water influences the process negatively. The longer duration of the convective dehydration can be thus explained, and, as a consequence, the increased input of electrical energy. At a temperature of the thermal agent of 60°C the input of electrical energy was 143.85 kW·h/kg evaporated water, and at 70, 80, 90, and 100°C it was 118.52, 81.39, 64.26, and 39.67 kW·h/kg evaporated water, respectively. In tab.1 the kinetic characteristics of the dehydration of blackcurrants are presented synthetically.

The comparison between the experimental coefficients of dehydration rate for the first interval \( (K_I) \) and the calculated ones for the mass transfer \( (\beta) \) is also of interest.
Kinetic characteristics of the blackcurrants convective dehydration process

<table>
<thead>
<tr>
<th>Temperature of thermal agent (°C)</th>
<th>( \frac{d_u}{d_t} ), (%/s)</th>
<th>( K_{l, %} ), (m²·s·kg/kg a.d.)</th>
<th>( K_{l, \frac{\text{s}^5}{(\text{m}^2\cdot\text{s}^3)\cdot\text{kg/kg a.d.}}} )</th>
<th>( \tau_{l1} ), (minute)</th>
<th>( \tau_{l1} ), (minute)</th>
<th>( \tau = \tau_{l1} + \tau_{l2} ), complete duration (minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.011</td>
<td>20.7</td>
<td>4.01</td>
<td>375</td>
<td>990</td>
<td>1365</td>
</tr>
<tr>
<td>70</td>
<td>0.012</td>
<td>21.3</td>
<td>4.86</td>
<td>345</td>
<td>735</td>
<td>1080</td>
</tr>
<tr>
<td>80</td>
<td>0.018</td>
<td>26.7</td>
<td>6.78</td>
<td>230</td>
<td>700</td>
<td>930</td>
</tr>
<tr>
<td>90</td>
<td>0.031</td>
<td>39.8</td>
<td>11.37</td>
<td>133</td>
<td>495</td>
<td>628</td>
</tr>
<tr>
<td>100</td>
<td>0.062</td>
<td>66.0</td>
<td>18.96</td>
<td>64</td>
<td>265</td>
<td>329</td>
</tr>
</tbody>
</table>

The literature in the field [4, 5] considers that during the interval of constant dehydration rate the intensity of the process is equal to the intensity of evaporation from the free surface, and the coefficient of water transfer depends on the speed and temperature of the thermal agent and on the conditions of the ventilation (regeneration) of the external surface of the fruit (blackcurrant) (shape and dimensions). At the same time the coefficient of water transfer is characterized by the Nusselt number \( (\text{Nu}_d) [4] \).

\[
\text{Nu}_d = A \cdot \text{Re}^n \cdot \text{Pr}_d^{0.33} \cdot \text{Gu}^{0.135}
\]

where:

\[
\text{Nu}_d = \beta \cdot 1 \cdot D_1 \quad (\text{Nusselt number});
\]

\[
\text{Re} = \omega \cdot l \cdot v^1 \quad (\text{Reynolds number});
\]

\[
\text{Pr}_d = v \cdot D^1 \quad (\text{Prandtl number});
\]

\[
\text{Gu} = (t_{us} - t_{um}) \cdot t_{um}^{-1} \quad (\text{Gukhman number})
\]

In order to compare the intensity of the coefficients of mass transfer \( \beta \) (m/s) with the coefficients of dehydration rate \( [K_l \%/s \cdot m^2 \cdot kg/kg dehydrating agent] \), these were evaluated with the relation:

\[
K_l' = K_l \cdot \frac{\Delta G}{\Delta u} \cdot \frac{l}{\rho}, \quad \text{where: } \frac{\Delta G}{\Delta u} = \frac{G_{um} - G_{er}}{u_{in} - u_{er}}
\]

In Tab. 2, the recalculated coefficients of dehydration rate in the first interval \( (K_l') \) and of mass transfer \( \beta \) are presented. It can be observed that the value of the coefficients of dehydration is lower than the calculated coefficients of mass transfer \( \beta \) except for the temperatures 90°C and 100°C.

<table>
<thead>
<tr>
<th>( t ), (°C)</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{l, %} ), (m²·s·kg/kg a.d.)</td>
<td>7.2</td>
<td>7.8</td>
<td>9.8</td>
<td>15.5</td>
<td>26.1</td>
</tr>
<tr>
<td>( \beta \cdot 10^3 ), (m/s)</td>
<td>13.7</td>
<td>14.1</td>
<td>14.6</td>
<td>15.0</td>
<td>15.3</td>
</tr>
</tbody>
</table>

The determined intensity of water transfer is lower than the calculated value \( \beta \). This demonstrates the presence in the blackcurrant fruit of a "diffusion resistance" to the mass transfer, which diminishes together with the increase of temperature and becomes null at 100°C. Elimination of the supplementary diffusion resistance in the boundary layer and the
intensification of the dehydration process was possible by accessing the unconventional dehydration methods (with microwaves).

In the variant with microwaves a magnetron with a nominal power (N) of 1.5 kW and a frequency of the electromagnetic field of 2450 MHz was employed. The mass deficit was recorded every minute.

From the analysis of the data in the literature it follows that the kinetic of dielectric dehydration does not differ essentially from the kinetic of dehydration by convection. The presence of some internal heat sources generates certain phenomena, which do not occur or have a considerable influence in the less intense dehydration processes.

The curves of blackcurrants dehydration \( u = f(\tau) \), with microwaves, was performed at four levels of the magnetron’s nominal power (25, 50, 75 and 100% N). It can be observed that the time of the dehydration of blackcurrants depends on the degree of the accession of the magnetron’s power. Thus, for 25% N the initial water content diminishes from 54% to 24% in 50 min, but together with the increase of the magnetron’s power to 50, 75 and 100% N the process unfolds acceleratedly (36, 28, and 20 minutes, respectively), i.e., the duration of the process decreases 2.5 times.

The analysis of the blackcurrants dehydration rate curves confirms the practical and theoretical considerations regarding the mass transfer mechanism in dehydration processes.

Thus, two intervals are evidenced: constant and variable rate. The first interval also represents about 40% of the total duration of the process for the dehydration of blackcurrants, while the second represents 60%. The water content evaporated in the first interval is about 62%, and 38% in the second. Comparing the convective and microwave dehydration it is observed, in the case of the latter variant, an increase of free moisture which is eliminated in the first interval (by 32% against the total water content, concomitantly with the extension of the duration of the first interval by 48% against the total duration of the process), most probably because the application of microwaves is contributing to the easier disconnection of water from the material, this moisture being osmotically bound to the material (lower association energy).

The increase of the magnetron’s power is accompanied by the doubling of the maximum value of the dehydration rate (it is 0.337%/s for 25%, and 0.667%/s at the nominal power).

Together with the increase of the magnetron’s power, the first critical point \( u_{cr} \) shifts to the right, namely: at 25% N \( u_{cr} \) corresponds to a 200% water content, and at 50, 75, and 100% N levels to 210, 240, and 250%, respectively. The general shape of the decreasing dehydration rate curves for different levels of the magnetron’s power differs insignificantly. The studies confirmed that, during the dielectric dehydration at high values of the magnetron’s power (75 and 100 % N), the heating of the wet material is more intense, so that the evaporation rate of the fluid exceeds considerably the diffusion rate of water, which is limited by the flow resistances due to the texture, structure of the plant material, a fact which is specified in all the cases reported and in the literature. Inside the fruit the gradient of general pressure also occurs as main driving force of the mass transfer process.

The influence of the level of accession of the magnetron’s power on the coefficient of dehydration in the second interval (\( K_u \)) is of exponential type.

In Tab. 3, the kinetic characteristics of the dielectric dehydration process for blackcurrants are presented. It is observed that, together with the increase of the magnetron’s power, the energy (electrical) input Q decreases 1.38 times due to the reduction of the dehydration time.
In the combined operating variant the presented processes were concomitantly performed for:

- five thermal regimes of the dehydrating agent in the range: 60-100°C;
- for levels of utilization the magnetron's power in the range: 25-100% N;
- six oscillation regimes: 5 s/25 s, 15 s/25 s, 25 s/25 s, 35 s/25 s, 45 s/25 s, 60 s/25 s, the first figure signifies the duration of the microwave impulse and the second the duration of the pause between two impulses. These ratios were expressed as the oscillation coefficient \( \tau' \) and belong to the series (0.2; 0.6; 1.0; 1.4; 1.8; 2.4).

<table>
<thead>
<tr>
<th>Power level (N%)</th>
<th>((\text{d}u/\text{d}t)_v) ((%/s))</th>
<th>(K_u \cdot 10^4) ((s^{-1}))</th>
<th>(\tau_I) (min.)</th>
<th>(\tau_II) (min.)</th>
<th>(\tau(\tau_I+\tau_II)) (min.)</th>
<th>(Q), (kW·h/kg evaporated water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.337</td>
<td>16.2</td>
<td>18</td>
<td>32</td>
<td>50</td>
<td>4.25</td>
</tr>
<tr>
<td>50</td>
<td>0.436</td>
<td>18.8</td>
<td>14</td>
<td>22</td>
<td>36</td>
<td>3.83</td>
</tr>
<tr>
<td>75</td>
<td>0.565</td>
<td>23.8</td>
<td>9</td>
<td>19</td>
<td>28</td>
<td>3.33</td>
</tr>
<tr>
<td>100</td>
<td>0.667</td>
<td>37.7</td>
<td>7</td>
<td>13</td>
<td>20</td>
<td>3.08</td>
</tr>
</tbody>
</table>

The recording of the weight decrease was done every minute for the speed of the dehydrating agent of 0.17 m/s.

In the paper the blackcurrants dehydration curves \(u = f(\tau)\) and dehydration rate curves, respectively, \(\left[ \frac{\text{d}u}{\text{d}\tau} = f(u) \right]\), in the combined variant, by convection and microwaves, was analyzed selectively. The shape of the curves matches the one described in the literature for colloidal capillary-porous materials. It can be also observed that the duration of the dehydration process depends on all the process parameters.

Knowing the dehydration curves \([u = f(\tau)]\) and the dehydration kinetics, respectively \(\left[ \frac{\text{d}u}{\text{d}\tau} = f(\tau) \right]\), the objective function was structured with the aid of linear programming with the adjacent restrictions in order to obtain the mathematic model of the dehydration of blackcurrants. In the resulting system of equations the minimization of the dehydration time was set initially, and later the maximization of the final water content of the dehydrated berries.

**CONCLUSIONS**

The convective, microwave, and combined dehydration of blackcurrants represents a technological variant for their medium- and long-term preservation, while maintaining their health benefits (vitamin C, carbohydrates) practically unchanged. Their mineral content increases, but within the limits of the European/international legislation. This phenomenon is caused by the concentration (dehydration) and not by the transfer of metal cations (mobile form) inside the trophic chain soil (water) – shrub – post-process fruit.

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