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Infrared drying of aronia berries: the effect of sustainable pretreatments on drying behavior

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This study investigates the infrared drying of aronia berries (*Aronia Melanocarpa*) and evaluates the effect of ultrasonic pretreatment on drying efficiency. Aronia berries are considered important functional foods due to their high antioxidant content and nutritional value. However, their short harvest season and limited shelf life hinder their commercialization. To address this, ultrasonic pretreatment was applied prior to drying to enhance process efficiency. Experiments were conducted at drying temperatures of 60°C, 70°C, and 80°C. For each temperature, aronia berries were subjected to ultrasonic pretreatment for 1, 3, 5, 10, 15, and 20 min before drying. Drying durations of pretreated samples were compared to those of untreated samples. Drying time and moisture content were measured, and the drying kinetics were analyzed. Kinetic parameters, including effective moisture diffusivity and activation energy were calculated, and the drying behavior was modeled using 14 commonly applied drying models used in the literature. The results demonstrated that ultrasonic pretreatment significantly enhanced drying performance, up to 10 min of pretreatment. The shortest drying time (120 min), highest effective moisture diffusivity ($1.20\cdot10^{-9}$ m^2/s) and highest activation energy (5137.6 J/mol) were obtained at 80°C infrared drying with 10 min of ultrasonic pretreatment.

Keywords: Aronia berry, drying kinetics, infrared drying, ultrasonic pretreatment

INTRODUCTION

Recently, there has been growing interest in fruits that are rich in natural antioxidants. Among them, aronia berries (*Aronia Melanocarpa*) stand out in the fields of food science and nutrition. This prominence is attributed to its exceptional concentrations of vitamins, minerals, polyphenols, flavonoids, and anthocyanins, as well as its potential to offer a wide range of health benefits. Aronia berries exhibit high antioxidant capacity and possess anti-inflammatory, anticancer, antimicrobial, antiviral, and antidiabetic properties. Furthermore, they have shown potential in inhibiting the development of some cancer types, such as colon cancer, breast cancer, leukemia, and even cancer stem cells. Their potential role in reducing the risk of cardiovascular disease has also been highlighted [1-5]. Beyond being a rich source of antioxidants, aronia berries hold great promise for applications in functional foods, nutraceuticals, and as a natural additive in the dairy, meat, and beverage industries [6-8]. Due to their high anthocyanin content, they exhibit a deep dark purple to black pigmentation, making them a valuable natural food colorant - particularly in products aimed at avoiding artificial additives [9, 10]. However, aronia berries have a very short harvest period, typically spanning from late summer to early fall. They also possess a high moisture content at the time of harvest, as they naturally thrive in wet habitats [1, 4]. As a result, they are prone to rapid deterioration, which significantly limits their shelf life. Therefore, it's crucial to implement effective preservation methods - not only to prolong shelf life, but also to maintain the functional and nutritional properties of the fruit. Drying stands out as one of the most efficient methods for food preservation.

Drying is the process of moisture removal from a substance, which helps slow down degradation and preserve quality. Under controlled conditions, moisture can be effectively removed from materials through drying, thereby preventing microbial growth and moisture-induced spoilage such as decay and mold. This is particularly important for food products with limited harvest periods, like aronia berries, as drying allows for better preservation of large quantities. Additionally, drying reduces product size, which lowers costs associated with packaging, transportation, storage, and processing, while also extending shelf life and enhancing product value [11-14]. However, the drying process is often time- and energy-intensive, as it requires the evaporation of water through the application of heat or airflow. It poses a particular challenge for berries, which are highly sensitive to heat and prone to the degradation of valuable bioactive compounds during dehydration. This challenge necessitates the exploration of new drying technologies that

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minimize such detrimental effects [11]. Infrared drying can be considered among these promising methods.

Infrared drying enables the uniform transfer of thermal energy in the form of electromagnetic radiation. In this method, heat is applied directly to the food as radiant energy [15]. Water is known to absorb infrared radiation strongly, causing the O–H bonds to vibrate upon energy absorption. This internal heating, which takes place very rapidly, increases the water vapor pressure within the food, resulting in pore expansion and a higher rate of moisture removal [15]. Infrared drying is capable of removing moisture quickly and efficiently. Apart from reducing drying times, it also offers benefits such as lower energy consumption, simpler equipment requirements, improved product quality, and reduced overall costs [11, 16, 17].

Berries are generally coated with a waxy protective layer that hinders moisture removal during drying. This barrier can be mitigated through pretreatment techniques that alter the fruit's surface structure. Such pretreatments help to reduce the drying time, and thereby the consumption of energy, while improving the overall quality of the food product [11]. Recently, sustainable thermal and non-thermal pretreatments have been developed to avoid the adverse effects of conventional approaches, such as nutrient loss, chemical absorption, and structural damage [11]. One such sustainable non-thermal technique is ultrasonic pretreatment.

Ultrasonic (US) pretreatment involves applying mechanical waves with frequencies between 20 kHz and 1000 kHz, typically using water or osmotic solutions as the medium in an ultrasonic bath [11-13]. These waves generate a cavitation phenomenon known as the "sponge effect," where alternating compression and expansion cycles create pressure gradients within the food. These gradients lead to the formation of microchannels inside the tissues of the plants, softening the food and facilitating moisture release through ruptured cell walls. Furthermore, ultrasonic treatment helps eliminate dissolved oxygen in intracellular spaces, which enhances both heat and mass transfer during drying [11-14]. In addition to shortening drying durations, ultrasonic pretreatment is recognized as a green, environmentally friendly, non-toxic, and safe technology. Its operation at ambient temperature is another advantage, helping to preserve the nutritional value and sensory qualities of the food product [11, 12, 16, 17].

Until now, studies on aronia berries have predominantly concentrated on the extraction of bioactive compounds and their antioxidant properties, with relatively limited emphasis on drying processes. However, understanding the drying behavior of aronia berries is crucial for researchers and industry stakeholders aiming to fully exploit their potential, particularly through innovative techniques such as infrared drying and sustainable pretreatments. This study, therefore, investigates the infrared drying behavior of aronia berries, incorporating ultrasonic pretreatment. Experiments were conducted at 60°C, 70°C, and 80°C drying temperatures. For each temperature, aronia berries were subjected to ultrasonic pretreatment for 1, 3, 5, 10, 15, and 20 min before drying. The drying behavior of the pretreated berry samples was compared with that of untreated ones. Parameters including moisture content, drying time, and drying rate were evaluated, and the data were analyzed in terms of drying kinetics. Kinetic parameters of effective moisture diffusivity (D_{eff}) and activation energy (E_a) were determined, and 14 commonly used drying models were applied to characterize the drying curves.

EXPERIMENTAL

Sample preparation

The aronia berries employed in this study were bought from a local farmers market in Bulgaria. Aronia berries of similar size, with an approximate radius of 0.55 cm, were selected for the experiments. In each trial, 5 ± 0.1 g of berries were used and cut into two halves horizontally to facilitate thin-layer diffusion analysis.

Experimental methods

The initial moisture content (M_0) was calculated through AOAC method [18], by drying the aronia berry samples in a hot air oven (KH-45, Kenton, Guangzhou, China) at 105°C, for 3 h. This procedure yielded an initial moisture content of 2.9373 kg water/kg dry matter (equivalent to 74.60% on wet basis).

For infrared drying, the aronia samples were initially weighed on tared aluminum plates using the scale of a Radwag MA 50.R infrared dryer (Radwag, Radom, Poland). After weighing, the aronia samples underwent ultrasonic pretreatment. The pretreatments prior to infrared drying experiments were made by using an Alex Machine AXUY-06LAB ultrasonic bath filled with distilled water and operating at 120 W (Isolab, Escau, Germany). The pretreatment durations were 1, 3, 5, 10, 15, and 20 min. After pretreatment, all samples were halved, reweighed, and the new measurement was recorded as the initial weight for drying. The infrared drying experiments were carried out at 60°C, 70°C, and

80°C. The sample weights were recorded every 15 min to track moisture loss and drying rate. Two repetitions were conducted for each condition, and the results were averaged. Drying was terminated once the moisture content reached 7%.

Kinetic calculations

The moisture content (M), moisture ratio (MR), and drying rate (DR) of the aronia berries at each experimental condition were calculated by using Equations 1, 2 and 3 [19-21]:

$$M = \frac{m_w}{m_d} \quad (1)$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (2)$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (3)$$

In Equation 1, m_w and m_d are the water content and the dry matter content of the aronia berries (kg), respectively. In Equations 2 and 3, t is the drying time (min), M_0 is the initial moisture content, M_e is the equilibrium moisture content, M_t is the moisture content at time t, and M_{t+dt} is the moisture content at the time t+dt (kg water/kg dry matter). Because of its relatively low value, M_e was neglected in the calculations [19, 20].

In this study, moisture diffusion for the drying process is modeled using Fick's second law of diffusion, based on several assumptions. These include negligible shrinkage, symmetrical moisture diffusion about the center, and constant diffusivity. Under these conditions, Fick's second law for moisture diffusion in a thin layer of thickness 2L is expressed as Equation 4 below [20, 22]:

$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} \times t}{4L^2}\right) \quad (4)$$

Here, n is a positive integer that is assumed as 1 for long drying durations. D_{eff} is the effective moisture diffusivity (m^2/s), L is one half of the thickness of the sample (m), and t is the time (s). With taking n as 1, Equation 4 can be rewritten in terms of Equation 5 in the linearized form [20, 22, 23]:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\pi^2 \frac{D_{eff} \times t}{4L^2}\right) \quad (5)$$

By using Equation 5, D_{eff} can be determined from the slope of the ln(MR) *versus* t graph. On the other hand, D_{eff} relation with temperature can be investigated through Arrhenius equation (Equation 6) given below [22, 24]:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R \times (T + 273.15)}\right) \quad (6)$$

In Equation 6, E_a is the activation energy (kJ/mol), D_0 is the preexponential factor (m^2/s), R is the universal gas constant (kJ/mol·K) and T is the drying temperature (°C). By using this equation, E_a can be determined from the slope of $\ln(D_{eff})$ *versus* 1/T graph. Evaluating activation energy is a key aspect of drying kinetics, as it represents the energy supplied by the drying system to facilitate moisture removal. Generally, higher activation energy indicates a more rapid drying process [22].

Mathematical modeling

Fourteen mathematical models commonly cited in the literature were evaluated to describe the drying behavior of aronia berries. These models are presented in Table 1.

Table 1. The mathematical drying models applied to the experimental data [20, 22]

Model name	Model equation
Aghbaslo *et al.*	$MR = \exp(-k_1 t / (1 + k_2 t))$
Alibas	$MR = a \times \exp((-kt^n) + bt) + g$
Henderson & Pabis	$MR = a \times \exp(-kt)$
Jena *et al.*	$MR = a \times \exp(-kt + b\sqrt{t}) + c$
Lewis	$MR = \exp(-kt)$
Logarithmic	$MR = a \times \exp(-kt) + c$
Midilli & Kucuk	$MR = a \times \exp(-kt^n) + bt$
Page	$MR = \exp(-kt^n)$
Parabolic	$MR = a + bt + ct^2$
Peleg	$MR = a + t/(k_1 + k_2 t)$
Two Term Exponential	$MR = a \times \exp(-kt) + (1-a) \times \exp(-kat)$
Verma *et al.*	$MR = a \times \exp(-kt) + (1-a) \times \exp(-gt)$
Wang & Singh	$MR = 1 + at + bt^2$
Weibull	$MR = a - b \times \exp(-(kt)^n)$

In Table 1, the coefficients used in the models include constants a, b, c, and g; the drying coefficients k, k_1, and k_2; model-specific exponent n; with drying time t in min. Nonlinear regression was performed using the Levenberg-Marquardt algorithm in Statistica 8 (Statsoft Inc., Tulsa, OK). The performance of the drying models was evaluated using the coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE), which are defined in Equations 7 to 9, respectively [22-24].

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - \left(\frac{1}{n}\right)MR_{exp,i}\right)^2} \quad (7)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (8)$$

$$RMSE = \left(\frac{1}{N}\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2\right)^{\frac{1}{2}} \quad (9)$$

In Equations 7-9, MR_{exp} and MR_{pre} are the experimental moisture ratios and predicted moisture ratios, respectively. N is the total number of experiments, and z is the number of constants that were used in the model equations. The mathematical model that gave the highest R^2, while giving the lowest χ^2 and RMSE, was selected as the most convenient model to describe the drying data of the aronia berries.

RESULTS AND DISCUSSION

Moisture content and drying rate results

Fig. 1 illustrates the changes of moisture content (on the left) and drying rate (on the right) of aronia berries dried at 60°C, 70°C, and 80°C without ultrasonic pretreatment. The initial moisture content of 2.9373 kg water/kg dry matter reduced to 0.2590, 0.1940, and 0.1808 kg water/kg dry matter at temperatures of 60°C, 70°C, and 80°C, respectively. The time required to reach final moisture content of 7% (wet basis) was 450 min at 60°C, 225 min at 70°C, and 165 min at 80°C.

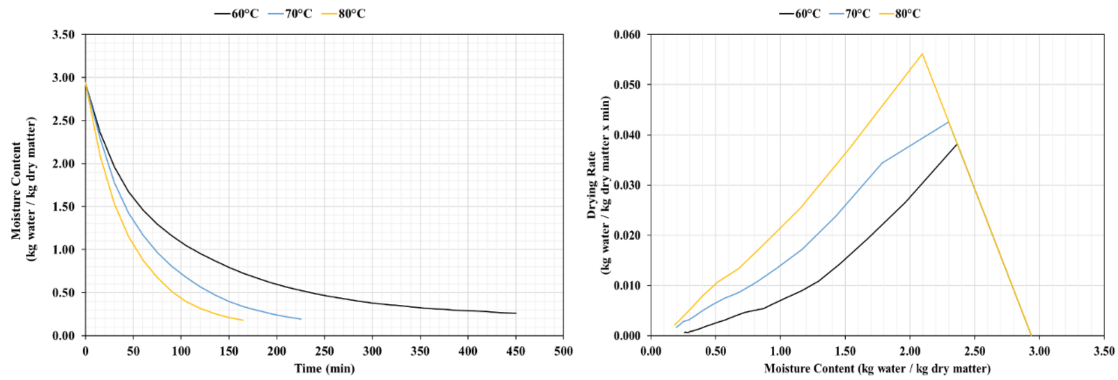

Fig. 1. Drying curves (left) and drying rate curves (right) for the infrared drying of aronia berries without pretreatment

The impact of ultrasonic pretreatment on drying performance is presented in Fig. 2, which shows the changes in moisture content and drying rate of aronia berries. In all graphs, results for 60°C are shown with black curves, whereas 70°C with blue, and 80°C with orange curves. Considering the effect of 1-min ultrasonic pretreatment (Fig. 2a), the initial moisture content of 2.9373 kg water/kg dry matter was reduced to 0.2021, 0.1927, and 0.1850 kg water/kg dry matter at 60°C, 70°C, and 80°C, respectively. The corresponding times to reach a final moisture content of 7% were 345 min at 60°C, 225 min at 70°C, and 165 min at 80°C. It was observed that 1 min of ultrasonic pretreatment significantly reduced the drying time at 60°C, while having no noticeable effect at 70°C and 80°C compared to the untreated drying times. As the ultrasonic pretreatment duration increased to 3 min (Fig. 2b), drying times further decreased at all temperatures. The drying durations were reduced to 315 min at 60°C, 210 min at 70°C, and 150 min at 80°C. A continued decrease in drying time was observed with a 5 min pretreatment (Fig. 2c), with drying times of 285 min at 60°C, 195 min at 70°C, and 120 min at 80°C. The final moisture contents were 0.1991, 0.1962, and 0.1881 kg water/kg dry matter, respectively.

Further increasing the ultrasonic pretreatment time to 10 min resulted in additional drying time reductions at 60°C (225 min) and 70°C (165 min), while the drying time at 80°C remained constant at 120 min. This ultrasonic duration yielded the shortest drying times across all pretreatment conditions. As presented in Fig. 2d, the final moisture contents of the aronia berries were 0.1992, 0.1718, and 0.1679 kg water/kg dry matter for 60, 70, and 80°C, respectively.

With a 15-min ultrasonic pretreatment, the initial moisture content of 2.9373 kg water/kg dry matter decreased to 0.2049, 0.1795, and 0.1433 kg water/kg dry matter at 60°C, 70°C, and 80°C, respectively. 240 min, 165 min, and 120 min were the drying durations at these temperatures. Compared to the 10-min ultrasonic pretreatment, a 15-min pretreatment resulted in a 15-min increase in drying time at 60°C, while no change was observed at 70°C and 80°C (Fig. 2e). Fig. 2f shows the effect of a 20-min ultrasonic pretreatment. The final moisture contents were 0.2010 kg water/kg dry matter at 60°C, 0.1939 at 70°C, and 0.1531 at 80°C. In the 60°C experiment, the drying time was observed to increase by 30 min, reaching 270 min. At 70°C, the drying duration increased to 180 min, whereas the drying time at 80°C remained unchanged at 120 min.

Overall, it can be concluded that increasing the ultrasonic pretreatment duration up to 10 min enhanced drying efficiency, particularly at lower drying temperatures. However, extending the pretreatment beyond 10 min resulted in a trend of increasing drying times at all temperatures, possibly due to changes in microstructure or moisture migration resistance.

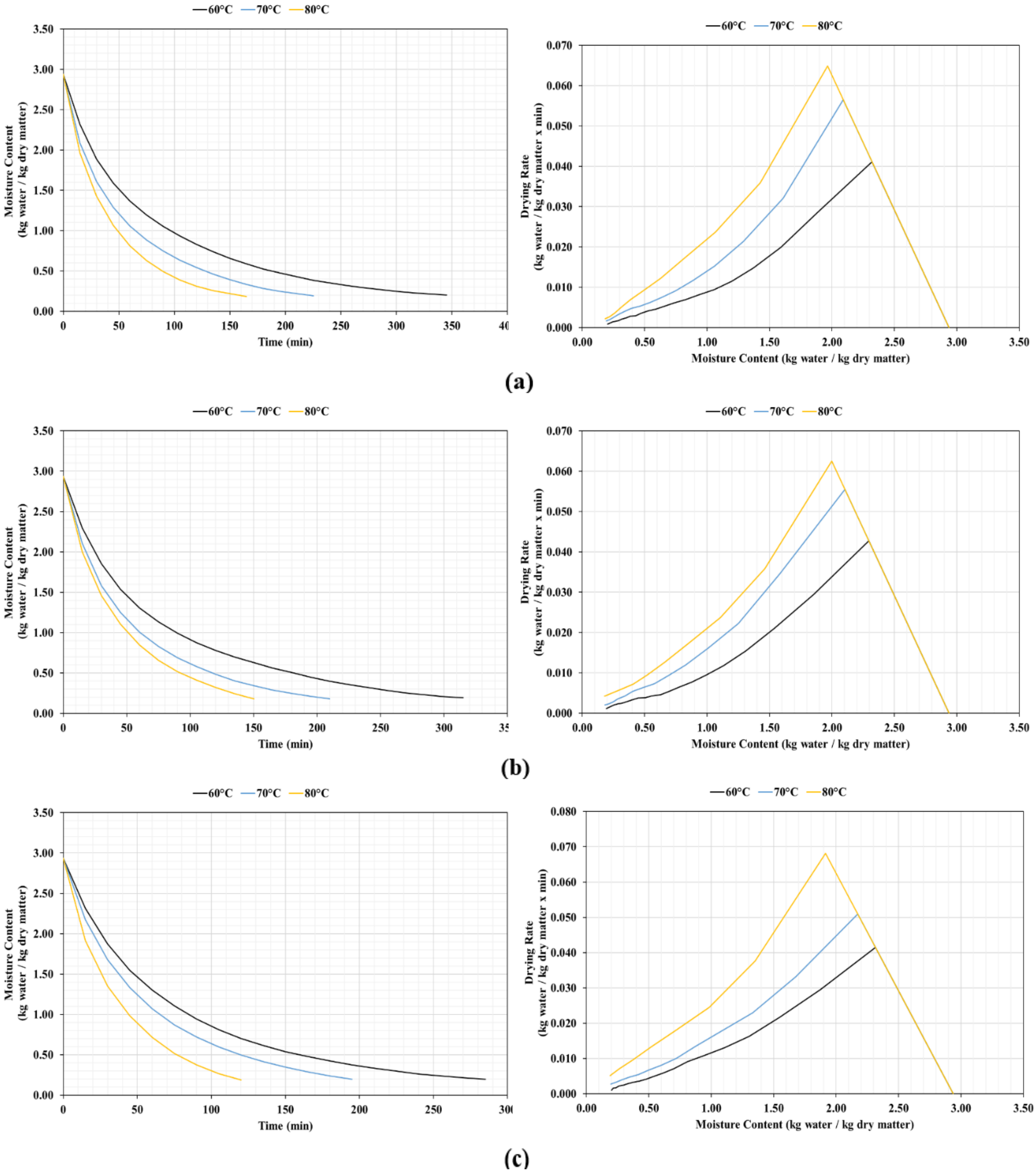

Fig. 2. The drying curves (left) and the drying rate curves (right) for the infrared drying of aronia berries with an ultrasonic pretreatment of (a) 1 min, (b) 3 min, and (c) 5 min

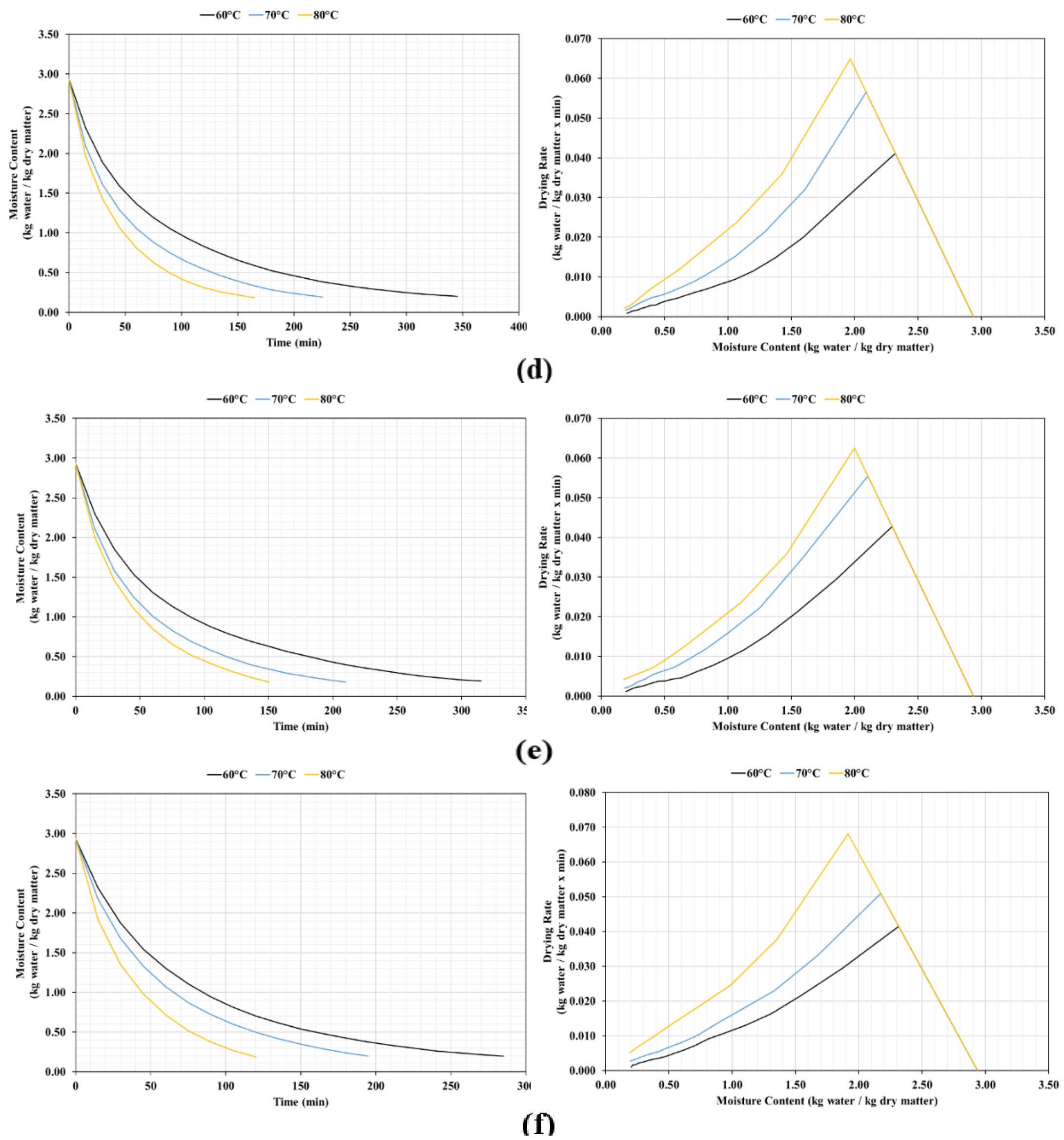

Fig. 2. (continued). The drying curves (left) and the drying rate curves (right) for the infrared drying of aronia berries with an ultrasonic pretreatment of (d) 10 min, (e) 15 min, and (f) 20 min

Several studies in the literature have investigated the impact of ultrasonic pretreatment on the drying behavior of agricultural products. Ni *et al*. [25] examined the influence of ultrasonic pretreatment, applied for durations ranging from 10 to 50 min, on the electrohydrodynamic drying of goji berries. The authors reported that ultrasonic pretreatment up to 30 min enhanced the drying rate. However, longer durations (40 and 50 min) caused a decrease in the drying rate, although all values remained lower than those of untreated samples. Yu *et al*. [26] investigated the effects of 2, 4, and 6 min of ultrasonic pretreatment on the hot air drying kinetics of *Camellia oleifera* seeds at 60 - 80°C. The experimental results showed that higher drying temperatures reduced drying time. While ultrasonic pretreatment also shortened drying time, the 2-min pretreatment duration was more effective than 4 or 6 min. The authors concluded that increasing pretreatment duration does not necessarily improve drying performance, as extended sonication may damage tissue structure and obstruct moisture migration pathways [26]. Similarly, Tan *et al.* [27] investigated ultrasonic-assisted alkali pretreatment in the hot air drying of seabuckthorn berries. Pretreatment durations of 5, 10, and 15 min resulted in drying time reductions of 5.08%, 3.06%, and 6.14%, respectively. These enhancements were said to be due to the dissolution of the waxy surface layer and the formation of micropores. However, prolonged ultrasonic pretreatment resulted in reduced drying rates, likely due to the disruption of moisture migration pathways on the berry surface caused by extended ultrasound exposure.

Fernandes and Rodrigues [28] examined the dehydration of sapota using ultrasonic pretreatment durations of 10, 20, and 30 min prior to oven drying at 60°C. A 5.2% water loss was observed for 10 min of pretreatment, which decreased to 4.0% with a 30 min duration. In a related work on the ultrasound assisted drying of pumpkin, Karlovic *et al*. [29] tested pretreatment durations of 30, 45, and 60 min. Increasing the pretreatment duration from 30 to 45 min reduced drying time across all ultrasound power levels, attributed to structural changes caused by cavitation. However, further extension to 60 min yielded only marginal improvements. The authors concluded that excessive pretreatment durations increase energy costs without significant benefits [29]. Salehi *et al.* [30] studied the impact of ultrasonic pretreatment (5, 10, and 15 min) on drying behavior of cooked faba beans at 70°C. They found that ultrasound enhanced water extraction by disrupting the diffusion boundary layer through rapid compressions and expansions. Sonication energy was also reported for weakening the intermolecular forces of bound water, breaking chemical bonds, thereby decreasing the resistance for mass transfer. In another study, Fernandes *et al.* [31] evaluated ultrasonic pretreatment durations ranging from 10 to 90 min in the air drying of papaya. An increase in water loss was observed with longer pretreatment durations, indicating a positive correlation between ultrasound exposure time and moisture removal.

Drying kinetics results

As discussed in the Experimental part, the effective moisture diffusivity (D_{eff}) values were determined using Equation 5, based on the slope of ln(MR) *versus* drying time graphs for all experimental data. Once D_{eff} was determined, the activation energy (E_a) for each pretreatment condition was found by using the linearized form of Equation 6, from the slope of ln(D_{eff}) *versus* 1/T plots. The results for all experimental conditions investigated in this study are summarized in Table 2. As presented in Table 2, the effective moisture diffusivity values increased with both increasing drying temperature and ultrasonic pretreatment duration up to 10 min. For infrared drying of aronia berries without pretreatment, D_{eff} values ranged between $2.57 \cdot 10^{-10}$ - $8.70 \cdot 10^{-10}$ m^2/s. With a 1 min ultrasonic pretreatment, this range increased to $3.80 \cdot 10^{-10}$ - $8.74 \cdot 10^{-10}$ m^2/s. Ultrasonic pretreatment effect was particularly pronounced at 60°C drying temperature, and this positive effect was observed up to 10 min of pretreatment. At this optimum pretreatment duration, D_{eff} was calculated as $5.95 \cdot 10^{-10}$ m^2/s at 60°C, $8.52 \cdot 10^{-10}$ m^2/s at 70°C, and $1.20 \cdot 10^{-9}$ m^2/s at 80°C, while latter being the highest D_{eff} value obtained in the present study.

Table 2. Drying times, D_{eff} and E_a values for the infrared drying of aronia berries

Pretreatment type	Drying parameter	60°C	70°C	80°C
Without pretreatment	Drying time (min)	450	225	165
	D_{eff} (m^2/s)	$2.57 \cdot 10^{-10}$	$6.10 \cdot 10^{-10}$	$8.70 \cdot 10^{-10}$
	E_a (J/mol)		4032.9	
1 min US pretreatment	Drying time (min)	345	225	165
	D_{eff} (m^2/s)	$3.80 \cdot 10^{-10}$	$6.13 \cdot 10^{-10}$	$8.74 \cdot 10^{-10}$
	E_a (J/mol)		4103.1	
3 min US pretreatment	Drying time (min)	315	210	150
	D_{eff} (m^2/s)	$4.20 \cdot 10^{-10}$	$6.53 \cdot 10^{-10}$	$9.13 \cdot 10^{-10}$
	E_a (J/mol)		4176.2	
5 min US pretreatment	Drying time (min)	285	195	120
	D_{eff} (m^2/s)	$4.72 \cdot 10^{-10}$	$6.83 \cdot 10^{-10}$	$1.14 \cdot 10^{-9}$
	E_a (J/mol)		4294.2	
10 min US pretreatment	Drying time (min)	225	165	120
	D_{eff} (m^2/s)	$5.95 \cdot 10^{-10}$	$8.52 \cdot 10^{-10}$	$1.20 \cdot 10^{-9}$
	E_a (J/mol)		5137.6	
15 min US pretreatment	Drying time (min)	240	165	120
	D_{eff} (m^2/s)	$5.46 \cdot 10^{-10}$	$8.43 \cdot 10^{-10}$	$1.18 \cdot 10^{-9}$
	E_a (J/mol)		4551.5	
20 min US pretreatment	Drying time (min)	270	180	120
	D_{eff} (m^2/s)	$4.71 \cdot 10^{-10}$	$7.54 \cdot 10^{-10}$	$1.17 \cdot 10^{-9}$
	E_a (J/mol)		4340.5	

For 15 and 20 min of pretreatment, D_{eff} values were observed to show a decreasing tendency. The activation energy values followed a similar trend. Without ultrasonic pretreatment, the activation energy was found as 4032.9 J/mol. The highest E_a value, 5137.6 J/mol, was recorded when a 10-min ultrasonic pretreatment was applied. However, when the pretreatment duration was increased further to 20 min, E_a decreased to 4340.5 J/mol.

Consistent findings have been reported in the literature regarding ultrasonic pretreatment's impact on effective moisture diffusivity. In the electrohydrodynamic drying of goji berries, Ni *et al.* [25] observed the highest D_{eff} value ($4.4573 \cdot 10^{-10}$ m^2/s) at a pretreatment duration of 20 min. Longer durations of 30, 40, and 50 min resulted in decreasing D_{eff} values. Similarly, Fernandes and Rodrigues [28] investigated the oven drying of sapota at 60°C, using ultrasonic pretreatment durations of 10, 20, and 30 min. The D_{eff} increased from $4.76 \cdot 10^{-9}$ m^2/s to $5.80 \cdot 10^{-9}$ m^2/s as the sonication duration increased from 10 to 20 min. However, extending the pretreatment to 30 min led to a slight decrease in D_{eff} to $5.38 \cdot 10^{-9}$ m^2/s. In a recent study, Salehi *et al*. [30] also reported a positive correlation between ultrasonic pretreatment time and D_{eff} values during the drying of faba beans, indicating improved moisture diffusivity with increased sonication duration.

Mathematical modeling results

The mathematical modeling results for the infrared drying of aronia berries, both with and without ultrasonic pretreatment, are presented in Table 3. The table displays the performance of the best-fitting model for each experimental condition, identified based on the highest coefficient of determination (R^2), and the lowest values of the reduced chi-square (χ^2) and the root mean square error (RMSE) among the 14 models evaluated.

Table 3. Statistical parameters of the best mathematical models for infrared drying of aronia berries, with and without ultrasonic pretreatment

Infrared drying, without pretreatment		
60°C	70°C	80°C
Parabolic a = 0.997162 b = -0.002657 c = 0.000002 R^2 = 0.999891 χ^2 = 0.000181 RMSE = 0.013056	Logarithmic a = 1.904526 k = 0.002245 c = -0.905562 R^2 = 0.999979 χ^2 = 0.000003 RMSE = 0.001634	Midilli & Kucuk a = 0.999604 k = 0.003781 n = 0.956175 b = -0.001353 R^2 = 0.999965 χ^2 = 0.000003 RMSE = 0.001458
Infrared drying, 1 min ultrasonic pretreatment		
60°C	70°C	80°C
Midilli & Kucuk a = 1.001346 k = 0.044791 n = 0.762047 b = 0.000016 R^2 = 0.999927 χ^2 = 0.000000 RMSE = 0.000420	Verma et al. a = 0.645558 k = 0.010447 g = 0.052267 R^2 = 0.999980 χ^2 = 0.000001 RMSE = 0.000994	Alibas a = 1.022881 k = 0.040817 n = 0.839702 b = 0.000204 g = -0.022830 R^2 = 0.999998 χ^2 = 0.000000 RMSE = 0.000532
Infrared drying, 3 min ultrasonic pretreatment		
60°C	70°C	80°C
Verma et al. a = 0.612461 k = 0.007166 g = 0.034810 R^2 = 0.999984 χ^2 = 0.000000 RMSE = 0.000672	Verma et al. a = 0.626539 k = 0.011200 g = 0.046393 R^2 = 0.999990 χ^2 = 0.000001 RMSE = 0.000673	Alibas a = 0.849635 k = 0.041469 n = 0.880241 b = -0.000780 g = 0.150360 R^2 = 0.999998 χ^2 = 0.000000 RMSE = 0.000486

Infrared drying, 5 min ultrasonic pretreatment		
60°C	70°C	80°C
Alibas a = 0.865617 k = 0.024311 n = 0.901521 b = -0.000303 g = 0.135035 R^2 = 0.999983 χ^2 = 0.000001 RMSE = 0.001122	Verma et al. a = 0.711448 k = 0.012051 g = 0.044981 R^2 = 0.999990 χ^2 = 0.000001 RMSE = 0.000817	Alibas a = 1.098238 k = 0.041008 n = 0.830144 b = 0.000316 g = -0.098187 R^2 = 0.999995 χ^2 = 0.000001 RMSE = 0.000723
Infrared drying, 10 min ultrasonic pretreatment		
60°C	70°C	80°C
Verma et al. a = 0.205842 k = 0.045454 g = 0.010960 R^2 = 0.999997 χ^2 = 0.000000 RMSE = 0.000096	Alibas a = 0.909268 k = 0.038373 n = 0.854349 b = -0.000479 g = 0.090911 R^2 = 0.999989 χ^2 = 0.000002 RMSE = 0.001147	Alibas a = 0.974563 k = 0.039675 n = 0.904756 b = -0.000132 g = 0.025408 R^2 = 0.999999 χ^2 = 0.000000 RMSE = 0.000371
Infrared drying, 15 min ultrasonic pretreatment		
60°C	70°C	80°C
Verma et al. a = 0.514585 k = 0.029105 g = 0.008158 R^2 = 0.999974 χ^2 = 0.000000 RMSE = 0.000166	Verma et al. a = 0.208568 k = 0.072575 g = 0.015577 R^2 = 0.999997 χ^2 = 0.000000 RMSE = 0.000536	Alibas a = 0.915657 k = 0.047883 n = 0.881610 b = -0.000587 g = 0.084308 R^2 = 0.999998 χ^2 = 0.000000 RMSE = 0.000481
Infrared drying, 20 min ultrasonic pretreatment		
60°C	70°C	80°C
Verma et al. a = 0.339860 k = 0.040146 g = 0.008482 R^2 = 0.999988 χ^2 = 0.000000 RMSE = 0.000409	Alibas a = 0.864808 k = 0.029947 n = 0.968746 b = -0.000434 g = 0.135342 R^2 = 0.999993 χ^2 = 0.000001 RMSE = 0.000879	Midilli & Kucuk a = 0.999741 k = 0.034798 n = 0.934494 b = 0.000032 R^2 = 0.999990 χ^2 = 0.000002 RMSE = 0.001079

CONCLUSION

This study investigated the effect of ultrasonic pretreatment durations (1, 3, 5, 10, 15, and 20 min) on the infrared drying of aronia berries at drying temperatures of 60°C, 70°C, and 80°C. Increasing drying temperature resulted in shorter drying times. Ultrasonic pretreatment also enhanced drying efficiency, particularly up to 10 min of application. For infrared drying without pretreatment, drying times ranged between 165 and 450 min. The application of short sonication durations notably reduced drying time, especially at lower temperatures. The shortest drying times (120-225 min) were obtained with 10 min of ultrasonic pretreatment. Beyond this duration, drying times increased at 60 and 70°C, while remaining unchanged at 80°C. A similar tendency was encountered for effective moisture diffusivity and activation energy. Without pretreatment, D_{eff} values ranged from $2.57 \cdot 10^{-10}$ - $8.70 \cdot 10^{-10}$ m^2/s. With 10 min of ultrasonic pretreatment, this range increased to $5.95 \cdot 10^{-10}$ - $1.20 \cdot 10^{-9}$ m^2/s. However, longer sonication durations resulted in a decrease in D_{eff}. Likewise, the activation energy increased from 4032.9 J/mol (no pretreatment) to 5137.6 J/mol with 10 min of pretreatment, before decreasing to 4350.5 J/mol at 20 min. Statistical analysis indicated that the models proposed by Verma *et al.,* Alibas, and Midilli & Kucuk best fit the experimental drying data.

Overall, it can be concluded that ultrasonic pretreatment of moderate durations improves the drying performance of aronia berries. As a safe, sustainable, and environmentally friendly technique, ultrasound can be effectively applied in infrared drying of aronia berries. However, excessive sonication should be avoided, as extended durations may lead to pore collapse, microchannel blockage, and hindered moisture migration, ultimately reducing drying efficiency.

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