

Comparative evaluation of infrared and microwave drying of berries: kinetics, diffusivity, and modeling approaches

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Berries are highly valued fruits which are widely cultivated for their distinctive flavor, rich nutritional composition, and health-promoting properties. However, despite their health benefits and nutritional merit, berries have a perishable nature due to their high moisture contents and delicate structures. Therefore, effective preservation methods are essential to extend their availability and reduce losses associated with microbial spoilage and seasonal production. Drying is a commonly employed preservation method which prolongs the shelf life while helping to retain nutritional quality and bioactive components. Although numerous studies have investigated changes in antioxidant capacity and nutritional composition during drying, research focusing on drying kinetics and mathematical modelling remains relatively limited. Therefore, the present study examines the infrared and microwave drying behavior of two types of berries: blueberries and golden berries. Infrared drying experiments were performed at temperatures of 60, 70, and 80°C, and microwave drying was carried out at power levels of 140, 210, and 350 W. For all experimental conditions, key kinetic parameters, along with effective moisture diffusivity values (D_{eff}) were determined. In addition, drying curves were analyzed using widely recognized mathematical models reported in the literature studies. Experimental results demonstrated that both drying methods are effective for the drying of blueberries and golden berries. The shortest drying times and the highest D_{eff} values were obtained at the highest infrared temperature and microwave power level.

Keywords: Blueberry; golden berry; infrared drying; microwave drying; mathematical modelling

INTRODUCTION

In recent years, berries have attracted increasing attention owing to their desirable taste and numerous health benefits. In addition, berries are rich in bioactive compounds that are associated with their anticarcinogenic and antioxidant properties. Blueberries and golden berries are among the berry fruits that have gained considerable consumer interest. Blueberries (*Vaccinium corymbosum*) are fruits characterized by their distinctive sweet-sour flavor and dark purple color. They are predominantly cultivated in regions of America and Europe. Blueberries are an important source of bioactive compounds, phenolic acids, flavonoids, vitamins, minerals, anthocyanins, and dietary fibers [1]. Furthermore, blueberries have been associated with protective effects against several diseases and health disorders, including Alzheimer's disease, urinary and cardiovascular diseases, muscular degeneration, diabetes, and cancer [2-5].

Golden berry (*Physalis peruviana*), on the other hand, is native to the Andean region of South America, where it has traditionally been cultivated [6, 7]. Also known as cape gooseberry, the fruit has a yellow-colored skin and is enclosed within a dry,

parchment-like husk known as the calyx, which provides protection against unfavorable climatic conditions, as well as birds and insects [8-10]. Similar to blueberries, golden berries have received considerable attention because of their nutritional composition and high content of bioactive compounds. They contain considerable amounts of vitamins, particularly vitamins A, B-complex, C, and K, as well as minerals, dietary fibers, ascorbic acid, polyphenols, and carotenoids [7-11]. Golden berries have also been reported to have traditional and potential therapeutic applications in the management of various conditions, including cancer, hypertension, hepatitis, asthma, dermatitis, and rheumatism [12-14]. The relatively high vitamin K content may contribute to health benefits associated with blood clotting and bone metabolism and has been linked to a reduced risk of cancer and cardiovascular diseases. Owing to their fructose content, golden berries have also been suggested as a suitable fruit option for people with diabetes [10, 13]. Despite their nutritional and health-related benefits, both berries have relatively limited seasonal availability. Their delicate structure makes them susceptible to mechanical damage, while their high perishability limits their storage lives [3, 5].

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Consequently, different food processing and preservation technologies have been employed to improve their shelf lives and maintain their quality during storage. Among these preservation techniques, drying is one of the most effective approaches. It involves the removal of moisture from a material, thereby slowing deterioration processes and helping to maintain product quality. Under regulated drying conditions, moisture can be efficiently removed from food products, reducing microbial growth and moisture-related deterioration, including decay and mold formation [15, 16]. This is particularly advantageous for food products with short harvesting seasons, as drying enables the preservation of large quantities of produce for extended periods. In addition, drying reduces product volume and weight, thereby decreasing packaging, processing, transportation, and storage costs while simultaneously improving the shelf life and increasing the overall value of the product [2, 17]. Nevertheless, traditional drying methods are slow and energy-demanding because they depend on heat and air flow to evaporate water. This creates a major problem for delicate berries, as high temperatures easily destroy their heat-sensitive, beneficial bioactive compounds. Consequently, exploring alternative options like infrared and microwave drying is essential to protect berry quality, while improving the drying performance.

Infrared drying facilitates thermal energy transfer to the product through electromagnetic radiation, enabling efficient and relatively uniform heating. In this technique, thermal energy is delivered directly to the food material in the form of radiant energy [18]. Water strongly absorbs infrared radiation, and the absorbed energy induces vibrational motion of the O-H bonds within water molecules. The rapid internal heating generated by this mechanism elevates the vapor pressure in the food material, promoting the expansion of pores and, consequently, accelerating moisture removal [18, 19]. As a result, infrared drying can achieve rapid and efficient moisture removal. In addition to shortening drying times, infrared drying provides several advantages, including simpler equipment design, more uniform product temperatures, improved product quality, reduced energy consumption, lower operating costs, and broad applicability to different food materials [15, 20-23].

Microwave drying, in contrast, uses electromagnetic radiation within the frequency range between 300 MHz and 300 GHz [21, 24]. This technology offers several important advantages because electromagnetic energy is directly absorbed by water molecules as a result of their dipolar nature

and subsequently converted into heat through molecular motion [16, 18, 25]. According to Feng *et al.* [24], the principal advantages of microwave drying are volumetric heating and generation of vapor within the product. Heating within the product promotes the development of internal vapor pressure, which facilitates the migration and removal of moisture from the material. Consequently, microwave drying can provide rapid drying with high energy efficiency, while contributing to better product quality and color retention, as well as safer handling and easier operation [21, 23, 24, 26]. In food drying applications, microwave drying is also frequently combined with conventional techniques, including hot-air and vacuum drying [14, 18]. Previous studies have shown that integrating microwave heating with conventional drying methods as a hybrid process can substantially reduce drying time and energy consumption, while increasing the drying rate and overall process efficiency [16, 21].

To date, research on berry drying has primarily focused on the extraction of bioactive materials and the evaluation of antioxidant activity, whereas comparatively limited attention has been given to the kinetic characteristics of the drying procedure. Considering the information presented above and the limited number of studies addressing drying kinetics, moisture diffusivity, and mathematical modelling, the present study investigated the infrared and microwave drying behavior of blueberries and golden berries. The experiments on infrared drying were performed at 60, 70, and 80°C, whereas microwave drying was performed at powers of 140, 210, and 350 W. For each experimental condition, drying time, moisture content, and drying rate were evaluated. Important kinetic parameters were subsequently calculated, including effective moisture diffusivity. Furthermore, 14 standard mathematical models from existing literature were used to fit the experimental drying curves. The results were then compared with the author's prior research on oven drying and vacuum oven drying of blueberries [27] and golden berries [28].

EXPERIMENTAL

Berry samples

The blueberries employed in this study were cultivated in Chile, while the golden berries were cultivated in Columbia. Both types of berries were purchased from a market in İstanbul. For each experimental run, 10 ± 0.1 g of berries with comparable dimensions were selected. The blueberries had an approximately 1.1 cm diameter, whereas the golden berries had an approximately 2.1

cm diameter. The berries were horizontally sectioned into two equal halves prior to the drying experiments to facilitate the investigation of thin layer moisture diffusion.

The initial moisture content of the berry samples were determined with respect to the AOAC method [29]. For this purpose, the berry samples were dried at 105°C in a hot-air oven for 4 h (KH - 45, Kenton, Guangzhou, China). Accordingly, the initial moisture content of the blueberries and golden berries was determined as 84.33% and 74.93% on wet basis, corresponding to 5.38 and 2.99 kg water/kg dry matter, respectively.

Experimental procedure

In the infrared drying experiments, a Radwag MA 50. R infrared dryer was employed, operating at 50 MHz and with 230 V (Radwag Balances and Scales, Radom, Poland). The drying experiments were performed at temperatures of 60, 70, and 80°C. Microwave drying experiments were conducted using an HMT72G420 model Bosch microwave oven, with dimensions of 530 × 500 × 322 mm (Robert Bosch Hausgeräte GmbH, Munich, Germany). The microwave oven operated at 2450 MHz and had a maximum power of 800 W. Drying experiments were performed at microwave powers of 140, 210, and 350 W.

During infrared drying, the sample weights were monitored at 15-min intervals throughout the process to calculate the moisture loss and corresponding drying rate. Owing to the considerably faster moisture removal observed during microwave drying, shorter weighing intervals were employed. Accordingly, the blueberry samples were weighed every 6 min, while the golden berry samples were weighed every 30 s, 20 s, and 10 s at microwave powers of 140, 210, and 350 W, respectively. The mean values obtained for three independent replicates at each experimental condition were used in the calculations. Drying was conducted across all experimental runs, until a final moisture content of 7% was attained.

Kinetic calculations

For each experimental condition the moisture content, M , the drying rate, DR , and the moisture ratio, MR were determined by using Equations (1), (2), and (3), respectively [15, 27, 28]:

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

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (2)$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (3)$$

In Equation (1), m_w and m_d are the water content of the berry samples and their dry matter content (kg), respectively. In Equation (2), t is the drying time in min, M_{t+dt} denotes the moisture content at the time $t+dt$, and M_t represents the moisture content at the time t (kg water/kg dry matter). In Equation (3), M_t , M_e , M_0 correspond to the moisture content at time t , the moisture content at equilibrium, and the initial moisture content, respectively, expressed as kg water/kg dry matter. Since M_e had a relatively low value, it was assumed to be negligible in the calculations [1, 30].

Moisture diffusion during drying was analyzed by Fick's 2nd law of diffusion. Application of this model was based on the assumptions of negligible sample shrinkage, symmetrical moisture diffusion with respect to the sample's center, and constant effective moisture diffusivity. With these assumptions, Fick's 2nd law of diffusion for moisture through a thin layer with a $2L$ thickness is given by Equation (4) [1, 19, 30]:

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

Here, n is positive and can be approximated as 1 for sufficient drying times. L corresponds to half of the sample thickness (m), D_{eff} is the effective moisture diffusivity (m^2/s), and t is the drying time (s). By considering $n = 1$, Equation (4) can be expressed in its linearized form as Equation (5) [1, 19, 30]. Accordingly, D_{eff} can be calculated through the slope of the linear relation between $\ln(MR)$ and drying time.

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

Mathematical modelling

To model the infrared and microwave drying behavior of blueberries and golden berries, experimental data were fitted to 14 standard mathematical models from existing literature. The 14 models considered in the analysis were given in the author's previous work [27, 28]. The model parameters were estimated *via* non-linear regression, through the Levenberg-Marquardt algorithm implemented in Statistica 8 program. The adequacy of each mathematical model was assessed using the coefficient of determination, root mean square error, and reduced chi-square, denoted by R^2 , $RMSE$, and χ^2 , respectively, which were determined through Equations (6), (7), and (8) [27, 31].

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^N (MR_{exp,i} - \frac{1}{N} \sum_{i=1}^N MR_{exp,i})^2} \quad (6)$$

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

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

In the above-mentioned equations, MR_{exp} and MR_{pre} represent the moisture ratios, which were determined experimentally and model-predicted, respectively. z represents the number of the constants that were employed in the corresponding model equations, whereas N denotes the number of the experiments considered. The mathematical model which provided the highest R^2 value, together with the lowest χ^2 and RMSE values was considered as the most suitable one for describing the drying behavior of the blueberries and golden berries.

RESULTS AND DISCUSSION

Infrared drying of blueberries and golden berries

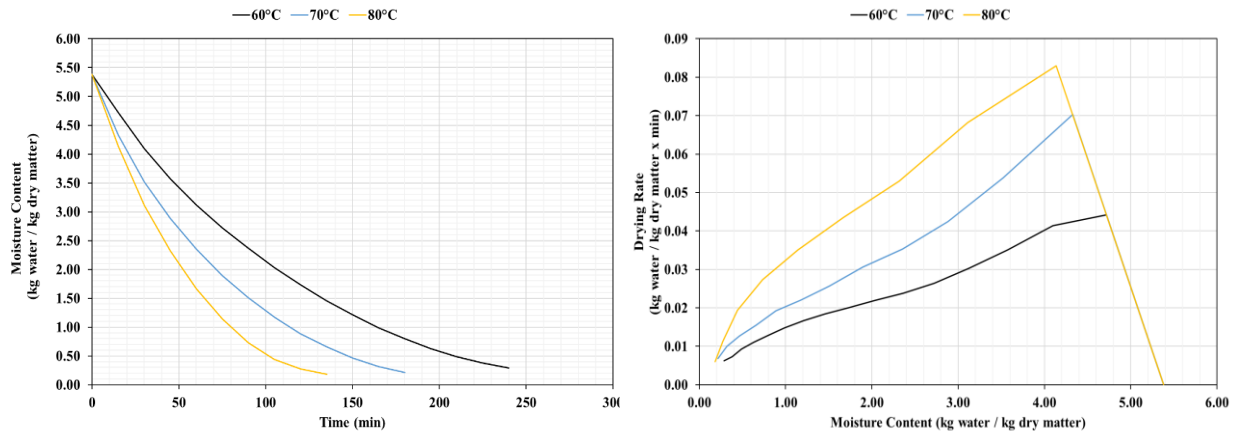


Figure 1. Variation of moisture contents and drying rates for the infrared drying of blueberries at 60, 70, and 80°C.

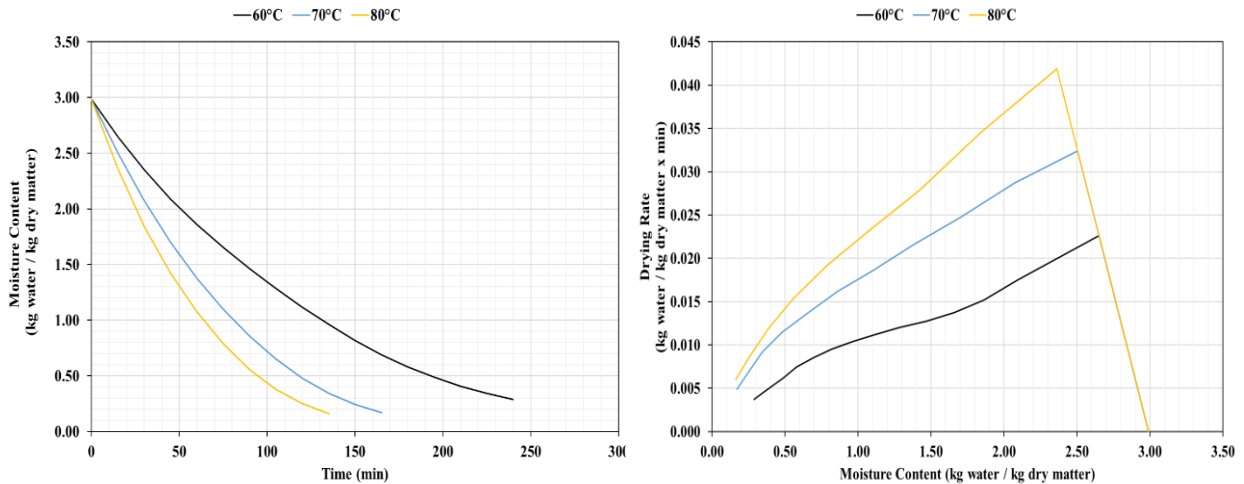


Figure 2. Variation of moisture contents and drying rates for the infrared drying of golden berries at 60, 70, and 80°C.

The results demonstrate that the berry type did not have a notable effect on the time required to reach the target final moisture content under infrared drying conditions. However, the drying temperature had a pronounced effect on the drying time for both berry types. The reduction in drying time with increasing temperature is consistent with findings reported in previous literature studies. For instance, Lopez *et al.*, investigated the influence of air-drying temperatures ranging from 50 to 90°C on the drying behavior of golden berries [9]. Accordingly, the time for reaching a moisture ratio of 0.1 decreased from approximately 800 min at 50°C to 180 min at 90°C. Similarly, Ozyalcin and Kipçak [31] investigated the infrared drying of squid and reported drying times of 277, 240, and 150 min at 60, 70, and 80°C, respectively. In another study, convective, infrared and freeze-drying of golden berry pulp were comparatively investigated [11]. Accordingly, increasing the temperature from 60°C to 80°C reduced the infrared drying time to reach below 0.078 g water/g dry matter from 630 to 450 min. Likewise, Zhang *et al.* [33] investigated ultrasonic-assisted infrared drying of ginger slices at 50, 60, and 70°C. When the temperature for drying increased from 50 to 70°C, the drying time decreased from 225 min to 105 min. The authors attributed this behavior to the increased energy absorbed by the samples at higher temperatures, thereby enhancing moisture removal and consequently accelerating the drying process.

When the drying rate curves are investigated, it is seen that higher drying temperatures resulted in faster drying rates. For both berries, the drying curves consisted primarily of rising-rate and falling-rate periods with no distinct constant-rate period. Puente *et al.* [11] attributed the absence of a constant-rate period to the waxy layer covering of the fruit surface

which may hinder moisture transfer from the fruit's interior to its surface. Similar behavior was reported by Doymaz during the infrared drying of red kidney bean seeds at various infrared power levels [15]. The drying rate was found to increase with increasing infrared power, no constant-rate period being observed. Kipçak and Doymaz [19] reported comparable results for the infrared drying of cherry tomatoes, where a distinct constant-rate period was absent. Likewise, in another study regarding the infrared drying of squid, it was reported that a falling-rate period was seen in the drying rate curves only, with drying rates increasing with respect to the drying temperature [31]. More recently, Uribe *et al.* [32] investigated the infrared, vacuum, hot air, and freeze-drying of blueberries, and reported that no constant-rate period was observed during infrared drying at 70°C. The authors suggested that the fast removal of the unbound water from the surface of the fruit may have resulted in a negligible constant-rate period.

Overall, the performance of infrared drying can also be evaluated by comparing the results obtained in this study with those reported in the author's previous studies on oven drying and vacuum oven drying of blueberries [27] and golden berries [28] under the same drying temperatures. Infrared drying resulted in considerably shorter drying times than both conventional oven and vacuum oven drying. The drying times were 420, 390, and 210 min for the oven drying and 240, 210, and 150 min for the vacuum oven drying at 60, 70, and 80°C, respectively for blueberries [27]. Similarly, for golden berries, drying times of 480, 300, and 285 min were obtained using oven drying, whereas vacuum oven drying required 435, 285, and 195 min at 60, 70, and 80°C, respectively [28]. These comparisons indicate that infrared drying can substantially accelerate the drying rate and reduce the overall processing time of both berry types.

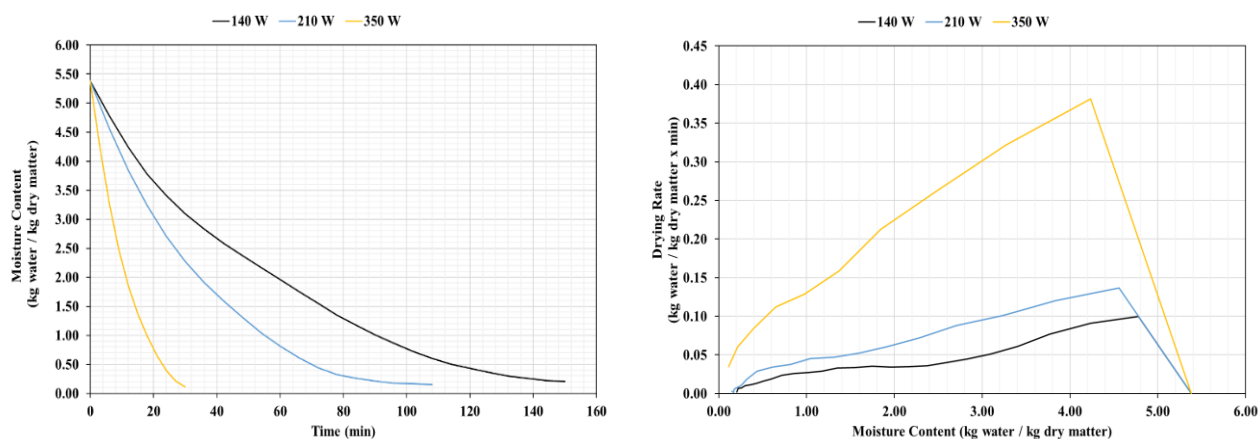


Figure 3. Variation of moisture content and drying rate for the microwave drying of blueberries at 140 W, 210 W, and 350 W.

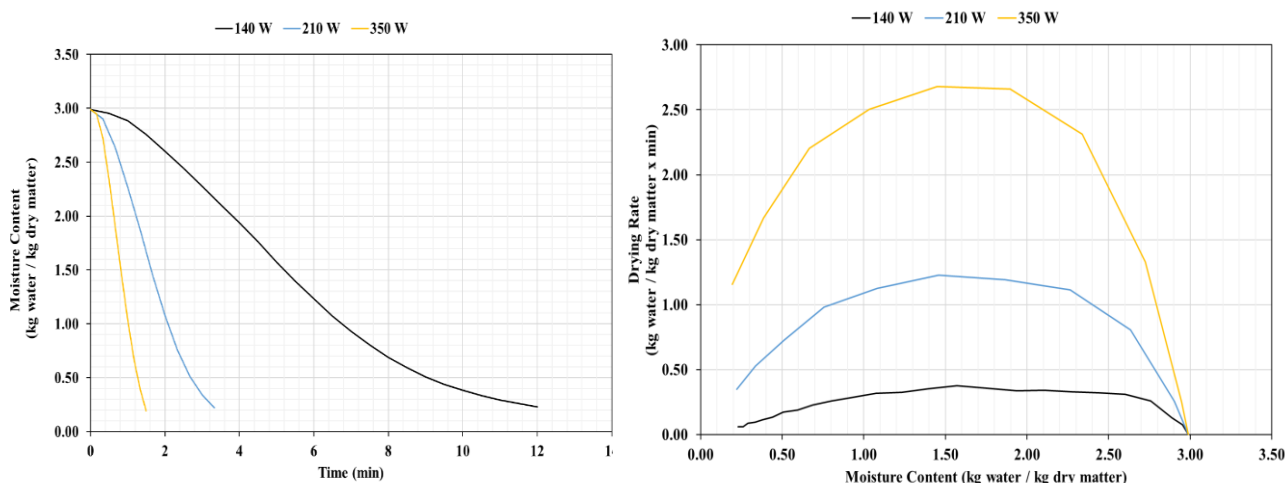


Figure 4. Variation of moisture content and drying rate for the microwave drying of golden berries at 140 W, 210 W, and 350 W.

Microwave drying of blueberries and golden berries

Figs. 3 and 4 display the moisture content curves (left) and drying rate curves (right) for blueberries and golden berries, respectively, during microwave drying across power levels of 140 W, 210 W, and 350 W.

As presented in Fig. 3 for the blueberry microwave drying, the initial moisture content of 5.3800 kg water/kg dry matter decreased to 0.2078, 0.1491, and 0.1104 kg water/kg dry matter at microwave powers of 140, 210, and 350 W, respectively. The corresponding drying times required to reach the 7% final moisture content were 150, 108, and 30 min. For the microwave drying of golden berries (Fig. 4) on the other hand, the initial moisture content of 2.9889 kg water/kg dry matter decreased to 0.2311, 0.2210, and 0.1941 kg water/kg dry matter at 140, 210, and 350 W, respectively. Attaining the target 7% final moisture content required drying times of 12 min (at 140 W), 3.3 min (at 210 W), and 1.5 min (at 350 W). A pronounced decrease in drying time was therefore observed for the microwave drying of golden berries. However, an important limitation was also observed at higher microwave power levels. At 210 W and 350 W, the golden berry samples burst and ruptured in all experimental replicates and were unable to retain their original shape. Such behavior was not observed during the microwave drying of blueberries. Examination of the drying rate curves showed that the drying rate increased with increasing microwave power. Similar to infrared drying, the drying curves of blueberries exhibited rising-rate and falling-rate periods, whereas a distinct constant-rate period was not observed.

The enhancement in drying rate with increasing microwave power is consistent with previous studies

on various food products. For instance, Beaudry *et al.* [25] investigated hot air, vacuum, microwave-assisted hot air, and freeze-drying of osmotically dehydrated cranberries. Among the aforementioned methods investigated, microwave-assisted drying produced the shortest drying times. In a study on microwave-dried tomato slices, Horuz *et al.* [34] reported that raising the microwave power from 120 W to 180 W reduced the time needed to reach a 17% moisture content from 636 min to 341 min. The authors attributed this reduction to an increase in the diffusivity of water within the tomato samples as microwave power increased. Moreover, no constant-rate period was encountered during drying. The high drying rates achieved under microwave heating were attributed to heat generation inside the sample, which produced a substantial vapor pressure gradient between the interior and surface of the tomatoes and thereby facilitated water removal from the tissue. Kıpçak and Doymaz [19] investigated the microwave drying of cherry tomatoes at microwave powers of 90, 180, 270, and 360 W. The required drying times to reach the final moisture content were 68, 34, 12, and 7 min, respectively. These drying times were considerably shorter than the drying times obtained during infrared drying, for which the corresponding drying times were 510, 390, and 330 min at infrared powers of 74, 88, and 104 W, respectively. In another study, in which the microwave drying of squid was examined, the drying times were reported as 18, 7, and 4.5 min for the microwave powers of 140, 210, and 350 W, respectively [31]. The authors also reported that only the falling-rate period could be identified in the corresponding drying curves.

The rupture observed in the golden berry samples during microwave drying may be associated with the highly waxy nature of their outer skin. This waxy layer can restrict migration of moisture from the

interior toward the surface, resulting in the accumulation of internal pressure within the fruit. Chen *et al.* [4] reported that when the internal pressure exceeds the mechanical strength of the epidermis, the fruit skin may crack or burst as a means of pressure release. Such behavior can subsequently result in structural collapse and deformation, adversely affecting the appearance of the dried product, as observed in the present study.

In addition to structural damage, other limitations associated with microwave drying have been reported. Belwal *et al.* identified scorching, particularly toward the end of drying with low moisture contents, as one of the major drawbacks of microwave drying [21]. Carranza-Conca *et al.* also reported cell disruption and rupture in microwave dried grapes, which was attributed to the elevated temperatures attained within the fruit [26]. Zhang *et al.* [33] noted that although microwave drying is a fast and potentially energy-efficient process, localized overheating may occur, resulting in burning or charring, particularly at the corners and edges of the material. Furthermore, microwave energy may damage the structure of the food materials, consequently impairing the rehydration characteristics of the dried product. Karam *et al.* similarly reported textural damage and subsequent scorching as potential disadvantages associated with microwave drying [16].

Drying kinetics

Understanding the drying kinetics of berries is significant for the effective design, operation, and optimization of drying processes, particularly when the preservation of product quality is considered. As described in the Experimental section, the effective moisture diffusivity (D_{eff}) was calculated by using Equation (5) for all experimental conditions

summarized in Table 1. As presented in Table 1, the values of D_{eff} increased with increasing drying temperature. A similar increase was observed with increasing microwave power. For both berry types, microwave drying resulted in considerably higher D_{eff} values than infrared drying. For blueberries, the D_{eff} values obtained by infrared drying ranged from $2.02 \cdot 10^{-9}$ to $4.32 \cdot 10^{-9} \text{ m}^2/\text{s}$, whereas microwave drying resulted in values ranging from $3.74 \cdot 10^{-9}$ to $2.02 \cdot 10^{-8} \text{ m}^2/\text{s}$. A similar trend was observed for golden berries. D_{eff} values ranged from $1.64 \cdot 10^{-9}$ to $3.61 \cdot 10^{-8} \text{ m}^2/\text{s}$ during infrared drying and increased to $3.89 \cdot 10^{-8}$ - $2.99 \cdot 10^{-7} \text{ m}^2/\text{s}$ during microwave drying. Comparison with the author's previous studies on the conventional oven drying and vacuum oven drying of blueberries and golden berries [27, 28] revealed different rankings of the drying methods regarding moisture diffusivity. For blueberries, the highest D_{eff} values were obtained during microwave drying, followed by vacuum oven, infrared, and oven drying. For golden berries, microwave drying also yielded the highest D_{eff} values, followed by infrared, vacuum oven, and oven drying. These results indicate that microwave heating substantially enhances internal moisture transport in both berry types.

Although relatively few studies have focused specifically on the kinetic evaluation of berry drying, the observed trends are consistent with findings reported for other food materials. For the infrared drying of squid at 60, 70 and 80°C, the corresponding D_{eff} values were found as $6.57 \cdot 10^{-10}$, $7.95 \cdot 10^{-10}$, and $1.35 \cdot 10^{-9} \text{ m}^2/\text{s}$, respectively [31]. Thus, D_{eff} increased with respect to infrared temperature. The same authors also investigated the microwave drying of squid at microwave powers of 140 W, 210 W, and 350 W, obtaining D_{eff} values of $1.25 \cdot 10^{-8}$, $3.52 \cdot 10^{-8}$, and $5.62 \cdot 10^{-8} \text{ m}^2/\text{s}$, respectively.

Table 1. Drying time and D_{eff} values for the infrared and microwave drying

Berry investigated	Drying method	Drying temperature/Power	Drying time (min)	D_{eff} (m^2/s)
Blueberry	Infrared drying	60°C	240	$2.02 \cdot 10^{-9}$
		70°C	180	$2.93 \cdot 10^{-9}$
		80°C	135	$4.32 \cdot 10^{-9}$
	Microwave drying	140 W	150	$3.74 \cdot 10^{-9}$
		210 W	108	$5.84 \cdot 10^{-9}$
		350 W	30	$2.02 \cdot 10^{-8}$
Golden berry	Infrared drying	60°C	240	$1.64 \cdot 10^{-9}$
		70°C	165	$2.80 \cdot 10^{-9}$
		80°C	135	$3.61 \cdot 10^{-8}$
	Microwave drying	140 W	12	$3.89 \cdot 10^{-8}$
		210 W	3.3	$1.35 \cdot 10^{-7}$
		350 W	1.5	$2.99 \cdot 10^{-7}$

For the drying of blueberries at 70°C, Uribe *et al.* [32] reported a higher D_{eff} for infrared drying ($1.61 \cdot 10^{-10} \text{ m}^2/\text{s}$) than for hot air drying ($1.40 \cdot 10^{-10} \text{ m}^2/\text{s}$). Similarly, Kipçak and Doymaz [19] reported a substantial increase in D_{eff} with microwave power during the microwave drying of cherry tomatoes. This behavior was attributed to the rapid increase in the sample temperatures under microwave heating, which increased the internal vapor pressure and consequently promoted faster moisture migration.

Mathematical modelling

Table 2 summarizes the mathematical modelling results for the infrared and microwave drying of blueberries and golden berries, highlighting the optimal fit among the 14 tested models for each condition. Model performance was evaluated using R^2 , RMSE, and χ^2 values, with the best model selected based on the highest R^2 , paired with the lowest RMSE and χ^2 values.

Table 2. Best-fitted mathematical models for the infrared drying and microwave drying of blueberries and golden berries

Infrared drying of blueberries		
60°C	70°C	80°C
Alibas	Logarithmic	Alibas
a = 2.46918	a = 1.07179	a = 4.19485
k = 0.00536	k = 0.01228	k = 0.00684
n = 0.94538	c = -0.07962	n = 0.97824
b = 0.00236	$R^2 = 0.99975$	b = 0.01036
g = -1.46791	$\chi^2 = 0.00003$	g = -3.19510
$R^2 = 0.99992$	RMSE = 0.00462	$R^2 = 0.99996$
$\chi^2 = 0.00001$		$\chi^2 = 0.00001$
RMSE = 0.00258		RMSE = 0.00204
Microwave drying of blueberries		
140 W	210 W	350 W
Midilli & Kucuk	Aghbashlo <i>et al.</i>	Aghbashlo <i>et al.</i>
a = 0.99019	$k_1 = 0.02618$	$k_1 = 0.07478$
k = 0.01887	$k_2 = -0.00276$	$k_2 = -0.01263$
n = 0.95409	$R^2 = 0.99893$	$R^2 = 0.99966$
b = -0.00059	$\chi^2 = 0.00010$	$\chi^2 = 0.00004$
$R^2 = 0.99854$	RMSE = 0.00956	RMSE = 0.00570
$\chi^2 = 0.00014$		
RMSE = 0.01068		
Infrared drying of golden berries		
60°C	70°C	80°C
Alibas	Alibas	Alibas
a = 2.80443	a = 3.02096	a = 3.19274
k = 0.00408	k = 0.00553	k = 0.00738
n = 0.96600	n = 0.99982	n = 0.97526
b = 0.00272	b = 0.00523	b = 0.00685
g = -1.80632	g = -2.02131	g = -2.19265
$R^2 = 0.99985$	$R^2 = 0.99998$	$R^2 = 0.99999$
$\chi^2 = 0.00002$	$\chi^2 = 0.00002$	$\chi^2 = 0.00001$
RMSE = 0.00333	RMSE = 0.00114	RMSE = 0.00073
Microwave drying of golden berries		
140 W	210 W	350 W
Alibas	Page	Page
a = 50.81750	k = 0.27400	k = 1.08259
k = 0.01950	n = 1.89164	n = 2.18701
n = 1.07660	$R^2 = 0.99994$	$R^2 = 0.99978$
b = 0.97020	$\chi^2 = 0.00001$	$\chi^2 = 0.00003$
g = -49.83200	RMSE = 0.00266	RMSE = 0.00503
$R^2 = 0.99955$		
$\chi^2 = 0.00006$		
RMSE = 0.00676		

CONCLUSION

In the present study, the drying behavior and kinetics of blueberries and golden berries using infrared and microwave drying methods under different operating conditions was investigated. The results demonstrated that both drying temperature and microwave power substantially affected moisture removal, drying rate, and effective moisture diffusivity. For infrared drying, increasing the drying temperature from 60°C to 80°C progressively accelerated moisture removal and reduced the time required to reach the final moisture content of 7%. The required drying times decreased from 240 min to 135 min for both blueberries and for golden berries. In addition, the drying curves of both berries were characterized mainly by rising-rate and falling-rate periods, with no distinct constant-rate period.

Microwave drying provided a considerably greater enhancement in drying performance. Increasing the power of the microwave from 140 to 350 W reduced the time required for the drying of blueberries from 150 to 30 min, while the corresponding drying time for golden berries decreased from 12 min to only 1.5 min. D_{eff} increased with increasing drying temperature during infrared drying and with increasing microwave power during microwave drying. Moreover, microwave drying resulted in substantially higher effective moisture diffusivity values than infrared drying for both berry types, indicating that volumetric microwave heating markedly enhanced internal moisture transport. Comparison with the conventional oven and vacuum oven drying results from the authors' previous studies further demonstrated the superior drying efficiency of infrared and, particularly, microwave drying.

Despite its remarkable drying rate, microwave drying presented an important limitation for golden berries. At 210 W and 350 W, the samples consistently ruptured and lost their original shape, whereas no comparable structural damage was observed in blueberries. This behavior may be associated with the waxy outer skin of golden berries, which can restrict moisture migration and promote internal pressure buildup during rapid microwave heating. Therefore, although higher microwave powers substantially improve drying efficiency, excessively intense microwave treatment may adversely affect the physical integrity and appearance of the product.

The results obtained for mathematical modeling showed that the drying behavior of both berry types could be described accurately using appropriate empirical models. Among the 14 models evaluated, Alibas model provided the best-fit for most infrared drying conditions, whereas different models,

including the Midilli & Kucuk, Aghbashlo *et al.*, Alibas, and Page models, provided the best representation under the microwave drying conditions. The selected models exhibited very high coefficients of determination and low χ^2 and RMSE values, demonstrating their suitability for describing the drying kinetics under the investigated conditions.

Overall, the findings indicate that microwave drying offers a substantial advantage in terms of moisture diffusivity and drying time, while infrared drying provides an effective alternative with considerably shorter processing times than conventional oven and vacuum oven drying. However, the optimum condition for drying should not be selected solely regarding the drying rate. In particular, the structural damage observed in golden berries at high microwave powers highlights the need to balance drying efficiency with product integrity. The results obtained in this study provide useful kinetic data and predictive models for the design, optimization, and potential scale-up of infrared and microwave drying processes for blueberries and golden berries.

REFERENCES

1. B. Gök, E. Kıpçak, *Bulg. Chem. Commun.*, **56** (3), 233 (2024).
2. A. Akcicek, E. Avci, Z. H. Tekin-Cakmak, M. Z. Kasapoglu, O. Sagdic, S. Karasu, *ACS Omega*, **8** (44), 41603 (2023).
3. K. An, M. Fu, H. Zhang, D. Tang, Y. Xu, G. Xiao, *J. Food Sci. Technol.*, **56** (2), 783 (2019).
4. F. Chen, M. Zhang, S. Devahastin, D. Yu, *Food Bioprocess. Technol.*, **14** (10), 1805 (2021).
5. M. Zielinska, A. Michalska, *Food Chem.*, **212**, 671 (2016).
6. L. Etzbach, M. Meinert, T. Faber, C. Klein, A. Schieber, F. Weber, *Curr. Res. Food Sci.*, **3**, 73 (2020).
7. J. R. de J. Junqueira, J. L. G. Corrêa, H. M. de Oliveira, R. Ivo Soares Avelar, L. A. Salles Pio, *LWT – Food Sci. Technol.*, **82**, 404 (2017).
8. K. Bravo, E. Osorio, *Food Chem.*, **197**, 185 (2016).
9. J. Lopez, A. Vega-Gálvez, M. J. Torres, R. Lemus Mondaca, I. Quispe-Fuentes, K. Di Scala, *Chil. J. Agric. Res.*, **73** (3), 293 (2013).
10. A. Nawirska-Olszańska, B. Stępień, A. Biesiada, J. Kolniak-Ostek, M. Oziębłowski, *Foods*, **6** (8), 60 (2017).
11. L. Puente, A. Vega-Gálvez, I. Fuentes, K. Stucken, A. Rodríguez, A. Pastén, *J. Food Sci. Technol.*, **58** (4), 1470 (2021).
12. E. Karacabey, *Braz. Arch. Biol. Technol.*, **59**, e16160470 (2016).
13. M. F. Ramadan, *Food Res. Int.*, **44** (7), 1830 (2011).
14. N. İzli, G. Yıldız, H. Ünal, E. Işık, V. Uylaşer, *Int. J. Food Sci. Technol.*, **49** (1), 9 (2014).

15. I. Doymaz, *J. Food Process. Preserv.*, **39** (6), 933 (2015).
16. M. C. Karam, J. Petit, D. Zimmer, E. B. Djantou, J. Scher, *J. Food Eng.*, **188**, 32 (2016).
17. S. H. Miraei Ashtiani, M. Rafiee, M. Mohebi Morad, A. Martynenko, *Drying Technol.*, **40** (8), 1639 (2022).
18. T. Skåra, T. Løvda, D. Skipnes, N. N. Mehlomakulu, C. R. Mapengo, R. O. Baah, M. N. Emmambux, *Food Rev. Int.*, **39** (9), 7197 (2023).
19. A. S. Kipcak, I. Doymaz, *Chem. Ind. Chem. Eng. Q.*, **26** (2), 203 (2020).
20. M. Pateiro, M. Vargas-Ramella, D. Franco, A. G. da Cruz, G. Zengin, M. Kumar, K. Dhama, J. M. Lorenzo, *Food Chem.: X*, **16**, 100465 (2022).
21. T. Belwal, C. Cravotto, M. A. Prieto, P. R. Venskutonis, M. Daglia, H. P. Devkota, A. Baldi, S. M. Ezzat, L. Gómez-Gómez, M. M. Salama, L. Campone, L. Rastrelli, J. Echave, S. M. Jafari, G. Cravotto, *Drying Technol.*, **40** (8), 1539 (2022).
22. Y. Sun, M. Zhang, A. Mujumdar, *Food Eng. Rev.*, **11** (1), 61 (2019).
23. C. Cui, D. Zhao, J. Huang, J. Hao, *Int. J. Food Prop.*, **25** (1), 435 (2022).
24. H. Feng, Y. Yin, J. Tang, *Food Eng. Rev.*, **4** (2), 89 (2012).
25. C. Beaudry, G. S. V. Raghavan, C. Ratti, T. J. Rennie, *Drying Technol.*, **22** (3), 521 (2004).
26. J. Carranza-Concha, M. Benlloch, M. M. Camacho, N. Martínez-Navarrete, *Food Bioprod. Process.*, **90** (2), 243 (2012).
27. E. Kıpçak, *Sigma J. Eng. Nat. Sci.*, **42** (3), 739 (2024).
28. E. Kıpçak, *J. Turk. Chem. Soc. Sect. B Chem. Eng.*, **6** (1), 1 (2023).
29. AOAC, *Official Methods of Analysis of AOAC International*, 16th edn., AOAC International, Rockville, MD, 1995.
30. B. Salık, A. Tan, E. Kıpçak, *Bulg. Chem. Commun.*, **57** (3), 235 (2025).
31. Z. O. Ozyalcin, A. S. Kipcak, *Turk. J. Fish. Aquat. Sci.*, **21** (3), 135 (2021).
32. E. Uribe, A. Vega-Galvez, A. Pasten, K. S. Ah-Hen, N. Mejias, L. Sepúlveda, J. Poblete, L. S. Gomez-Perez, *Antioxidants*, **13** (12), 1554 (2024).
33. D. Zhang, D. Huang, Y. Zhang, Y. Lu, S. Huang, G. Gong, L. Li, *Ultrason. Sonochem.*, **92**, 106287 (2023).
34. E. Horuz, H. J. Jaafar, M. Maskan, *Drying Technol.*, **35** (7), 849 (2017).