The effect of chemical pretreatment on the drying behavior of blueberries

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Blueberries (*Vaccinium corymbosum*) are small, blue, perishable fruits, which are packed with nutrients, minerals, organic acids and polyphenols. Additionally, blueberries are notable for their antioxidant properties, which can help to reduce the negative effects of diseases such as cancer and diabetes. However, they are seasonally produced and have short shelf life, so drying is an effective preservation method. Drying processes often include physical or chemical pretreatments to improve the quality of the dried fruit and shorten the drying time. While there are many studies on the antioxidant capacity and nutritional content of blueberries, research on their detailed drying behavior and the effects of different pretreatments is still limited. This study explores the impact of chemical pretreatment with K_2CO_3 solutions on the infrared and vacuum oven drying of blueberries. Blueberry samples were treated with these solutions at 30°C and 60°C before drying. Each pretreatment involved immersing the blueberries in the K_2CO_3 solutions for 1 and 3 min. After the pretreatments, drying was conducted at temperatures of 70°C and 80°C using infrared and vacuum oven methods. The drying behavior of the pretreated blueberries was compared to that of untreated samples. Effective moisture diffusivities (D_{eff}) were calculated, and the drying curves were modeled using 14 established mathematical equations. The results showed that the use of vacuum oven provided faster drying and K_2CO_3 pretreatments reduced drying time. 1 min dipping of the blueberries in a 30°C K_2CO_3 solution caused the most prominent decrease in the drying time and increase in the D_{eff} values. However, further contact of the blueberries at the foresaid solution temperature, and increasing the solution temperature at this dipping time did not cause a major change in the drying performance.

Keywords: Blueberry; infrared drying; vacuum oven drying; K_2CO_3; chemical pretreatment

INTRODUCTION

Blueberries (*Vaccinium corymbosum*) are small, round, dark purple fruits with a sweet-sour taste [1]. They are mainly grown in America, with the United States being the leading producer, as well as in Europe [2]. Blueberries are rich sources of vitamins, minerals, anthocyanins, phenolic acids, proanthocyanidins, flavonoids and dietary fibers. They are among the fruits highest in vitamin C and antioxidants, giving them protective properties against numerous diseases such as cardiovascular and urinary diseases, Alzheimer's disease, aging, muscular degeneration, vision problems, diabetes and cancer [1-5]. Blueberries are described as the "natural health package" by Li *et al*. [6], due to all of the aforementioned physiological functions and enhancing human immunity. However, blueberries are only available seasonally, are delicate and prone to mechanical damage, and perish quickly [1, 3, 5]. Therefore, various food processing technologies are used to extend their shelf lives and to improve their preservation.

Drying is a commonly used method to preserve food products, by reducing their water content to prevent harmful microbial and physicochemical reactions and inhibit enzymatic activities. This method is crucial in food science due to its numerous benefits, such as allowing safe storage over an extended period and reducing packaging and transportation costs due to decreased weight and volume [5, 7-10]. Additionally, dried fruits maintain or even enhance their nutritional values, making them excellent alternatives and useful additives in various food products [11]. However, drying is a time and energy intensive process, prompting the exploration of additional measures to optimize its use. Pretreatment processes are one of such measures, as they can decrease the time of drying, lower the consumption of energy, and maintain the quality of food products [8, 12, 13]. Moreover some food products, especially berries, are known to have a waxy outer layer that protects them from withering in ambient conditions. This condition obstructs the application of the drying processes [4, 14, 15]. Physical and chemical pretreatments are commonly used to remove the foresaid waxy outer layer to enhance the drying efficiency. However, chemical pretreatments have a major advantage over the physical ones, as they require a very short contact time to increase the rate of dehydration. Literature studies demonstrate that potassium carbonate (K_2CO_3), potassium hydroxide (KOH), potassium

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metabisulfite ($K_2S_2O_5$), sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3), ethyl oleate ($C_{20}H_{38}O_2$), ascorbic acid ($C_6H_8O_6$) and citric acid ($C_6H_8O_7$) are the most common chemicals that are used in the pretreatment solutions [10, 13-17]. Among the aforementioned chemicals, K_2CO_3 has been reported to successfully enhance the removal of the waxy outer layer and thereby lower the internal resistance for the diffusion of water [18]. Moreover, as a food additive, the use of K_2CO_3 has been approved by the Turkish Food Codex Regulation. Hence, it is accepted as not to pose a risk regarding human health [13].

In the literature there are many articles that examine how drying affects the nutritional contents and the antioxidant capacities of blueberries. However, there is a lack of studies exploring how different pretreatment conditions impact the drying process and its kinetics. To address this gap, this study investigates the effects of K_2CO_3 chemical pretreatment on the infrared drying and vacuum oven drying of blueberries. During the experiments, blueberry samples were subjected to K_2CO_3 solutions at 30°C and 60°C prior to drying. Furthermore, at each pretreatment temperature, the blueberries were contacted with the K_2CO_3 solutions for 1 min and 3 min, respectively. Following the chemical pretreatments, the infrared drying and vacuum oven drying of the samples were carried out at 70°C and 80°C. The effects of the aforementioned pretreatments on the drying behavior of blueberries were compared to those of untreated dried samples, and the effective moisture diffusivities (D_{eff}) were determined. Additionally, the experimental drying data was modeled using the 14 most well-known mathematical modeling equations from the literature.

EXPERIMENTAL

Preparation of the samples

The blueberries used in the experiments were imported from Peru and were obtained from a market in Istanbul. Blueberries of similar size, each with a radius of about 1 cm, were chosen and cut horizontally into two halves to study thin layer diffusion. In every experiment, 5 g of blueberries were dried. Before drying, the initial moisture content (M_0) of the blueberries was measured using the AOAC method [19], which involved drying them for 3 hours in a hot air-drying oven at 105°C (KH-45, Kenton, Guangzhou, China). The initial moisture content of the untreated blueberries was found as 4.2632 kg water/kg dry matter, or 81% on a wet basis.

- *Experimental methods.* The vacuum oven drying experiments were carried out at a Nüve EV-018 model oven (Nüve, Ankara, Turkey). Here, the vacuum assistance was supplied through a vacuum pump of KNF N022AN.18 model (KNF, Freiburg, Germany). During the experiments, the oven pressure was measured as 0.3 atm. For the infrared drying experiments, on the other hand, Radwag MA 50.R model infrared dryer that worked with 230 V at 50 MHz was used (Radwag Balances and Scales, Radom, Poland).

For the chemical pretreatments, K_2CO_3 solutions were prepared by adding 25 g of K_2CO_3, 2.5 g of olive oil and distilled water to reach the desired solution volume of 500 ml. During the experiments, blueberry samples were treated with K_2CO_3 solutions at temperatures of 30°C and 60°C before drying. Additionally, at each temperature, the blueberries were exposed to the K_2CO_3 solutions for 1 min and 3 min, respectively.

To designate the drying kinetic parameters, experiments were conducted at temperatures of 70° and 80°C. Blueberry samples were weighed every 15 min to measure their moisture contents. A digital balance with a precision of 0.001 g was used for weighing (AS 220.R2, Radwag, Radom, Poland). Two identical experiments were performed for each drying condition, and the drying process was concluded when the weight of the blueberries decreased to approximately 5% of their initial moisture contents.

- *Determination of the drying parameters.* To generate the drying curves, the moisture content (M), drying rate (DR) and moisture ratio (MR) for each experimental condition need to be calculated. These parameters were determined through Eqns. 1, 2 and 3 provided below [16, 20, 21]:

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

In the aforementioned equation M is the moisture content (kg water/kg dry matter). The water content and the dry matter content of the blueberries are represented with m_w and m_d, respectively (kg).

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

Eqn. 2 defines DR as the drying rate (kg water/kg dry matter·min), where t is the drying time (min), M_t and M_{t+dt} are the moisture contents at times t and t+dt, respectively (kg water/kg dry matter).

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

In Eqn. 3, MR represents the dimensionless moisture ratio. Here, M_t, M_e and M_0 are the instantaneous moisture content at time t, the equilibrium moisture content and the initial moisture content, respectively (kg water/kg dry matter). Due to the low moisture content at equilibrium (M_e) compared to the initial and instantaneous values, it is omitted in the calculations [20, 21].

In order to describe moisture diffusion during the drying process of food products, Fick's 2[nd] law of diffusion is applied. In this study, some assumptions were made to solve the equation. Firstly, the shrinkage of the blueberries was ignored. Additionally, it was assumed that symmetrical mass transfer occurred from the center solely through diffusion, with constant diffusivity. Based on these assumptions, Fick's 2[nd] law for a thin layer of thickness 2L is modified to Eqn. 4 [16, 21, 22]:

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

In Eqn. 4, D_{eff} represents the effective moisture diffusivity (m^2/s), t denotes time (s), L is half the thickness of the blueberry sample (m) and n is a positive integer. For extended drying durations, n is typically assumed to be 1 [21, 22]. Thus, Eqn. 4 can be simplified to Eqn. 5. Using Eqn. 5, D_{eff} can be computed from ln(MR) *versus* t plot's slope, as described below:

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

- *Mathematical modeling.* During the drying of the blueberries, 14 drying models from the literature were tested for mathematical modeling. The drying models applied to the experimental data, along with their equations, are presented in Table 1.

Table 1. Drying models applied to the experimental data [21]

Model Name	Model Equation
Page	MR = exp $(-kt^n)$
Peleg	MR = a + t/$(k_1 + k_2t)$
Lewis	MR = exp $(-kt)$
Alibas	MR = a×exp $((-kt^n) + bt) + g$
Weibull	MR = exp $(-(t/b)^a)$
Parabolic	MR = $a + bt + ct^2$
Jena *et al.*	MR = a×exp $(-kt + b\sqrt{t}) + c$
Verma *et al.*	MR = a×exp $(-kt)$ + $(1-a)$ × exp $(-gt)$
Logarithmic	MR = a × exp $(-kt) + c$
Aghbaslo *et al.*	MR = exp $(-k_1t / (1 + k_2t))$
Wang & Singh	MR = 1 + at + bt^2
Midilli & Kucuk	MR = a×exp $(-kt^n) + bt$
Henderson & Pabis	MR = a×exp $(-kt)$
Two-Term Exponential	MR = a×exp($-kt$)+ (1-a)×exp($-kat$)

For the models presented in Table 1, t represents time (min) and a, b, c and g are coefficients. The drying exponent specific to each equation is represented by n; and the drying coefficients are represented by k, k_1 and k_2. Statistica 7.0 software was employed for the nonlinear Levenberg-Marquardt procedure regressions in the modeling process (Statsoft Inc., Tulsa, OK). The fitting of the models to the drying data was evaluated based on the coefficient of determination (R^2, Eqn. 6), reduced chi-square (χ^2, Eqn. 7) and root mean square error (RMSE, Eqn. 8) values [10, 16, 21, 23].

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

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

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

In these equations, N represents the number of experiments, z denotes the number of constants in the model equations, and MR_{exp} and MR_{pre} indicate the experimental moisture ratios and the predicted moisture ratios, respectively. The model chosen as the most suitable was the one with the highest R^2, the lowest χ^2, and the lowest RMSE values.

RESULTS AND DISCUSSION

Moisture content and effective moisture diffusivity

The drying curves that demonstrate the moisture content change (M) with respect to time for the 70°C and 80°C infrared drying of blueberries at are presented in Fig. 1. Here, Fig. 1a presents the results without any pretreatment; Figs. 1b and 1c present the results for the blueberry samples dipped in 30°C K_2CO_3 solution for 1 min and 3 min, respectively; and Fig. 1d and 1e present the results for the blueberry samples dipped in 60°C K_2CO_3 solution for 1 min and 3 min, respectively, during infrared drying. Considering Fig. 1a, for the drying of blueberries without any pretreatment, the initial moisture content of 4.2632 kg water/kg dry matter was seen to decrease to 0.1871 and 0.0933 at 70°C and 80°C, respectively. For the weight of the blueberry samples to reach approximately 5% of their initial moisture contents, it took 255 min at 70°C and 135 min at 80°C drying conditions. When the samples were dipped in a 30°C K_2CO_3 solution for 1 min (Fig. 1b), the drying durations were found to decrease to 210 and 105 min at 70°C and 80°C, respectively. However, further contact of the blueberry samples with the 30°C K_2CO_3 solution for 3 min did not cause any change in the drying times (Fig. 1c). Accordingly, the drying time remained as

210 min at 70°C and there was a minor increase to 120 min at 80°C. At these conditions, the initial moisture content of 4.2632 kg water/kg dry matter decreased to 0.2022 kg water/kg dry matter at 70°C and to 0.1290 kg water/kg dry matter at 80°C. Increasing the K_2CO_3 pretreatment solution's temperature to 60°C did not show a distinct change in the drying durations for a 1 min contact time (Fig. 1d), which were 225 min for 70°C and 105 min for 80°C infrared drying temperatures. The initial moisture content of 4.2632 kg water/kg dry matter was seen to reduce to 0.2367 and 0.1734 kg water/kg dry matter at 70°C and 80°C, respectively. However, when the contact time with the K_2CO_3 pretreatment solution was increased to 3 min, as it can be observed from Fig. 1e, the drying durations reached the shortest values of the infrared experiments (165 min for 70°C and 90 min for 80°C).

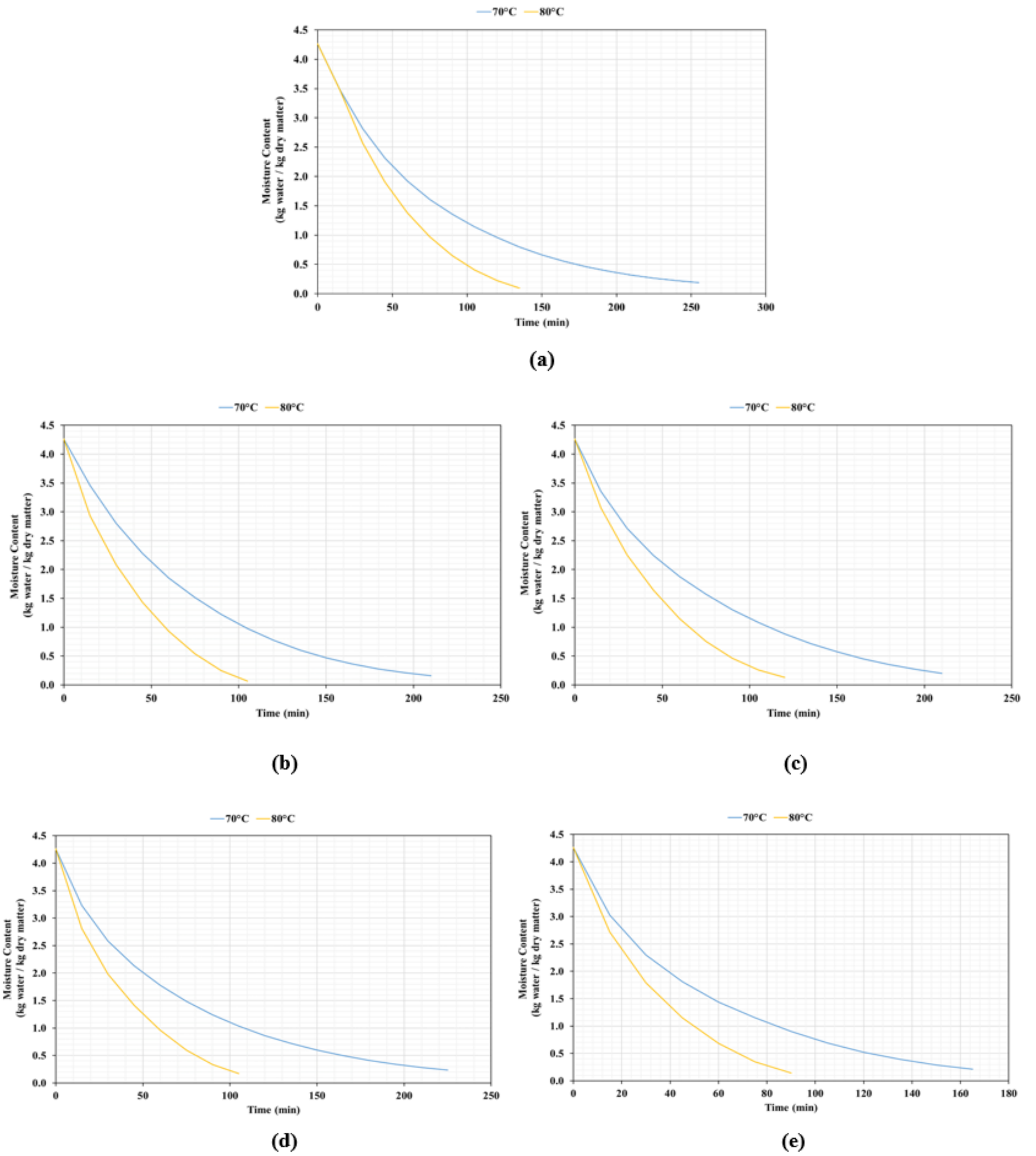

Fig. 1. The change in moisture contents of blueberries for infrared drying (a) without any pretreatment, (b) 30°C, 1 min K_2CO_3 pretreatment, (c) 30°C, 3 min K_2CO_3 pretreatment, (d) 60°C, 1 min K_2CO_3 pretreatment (e): 60°C, 3 min K_2CO_3 pretreatment

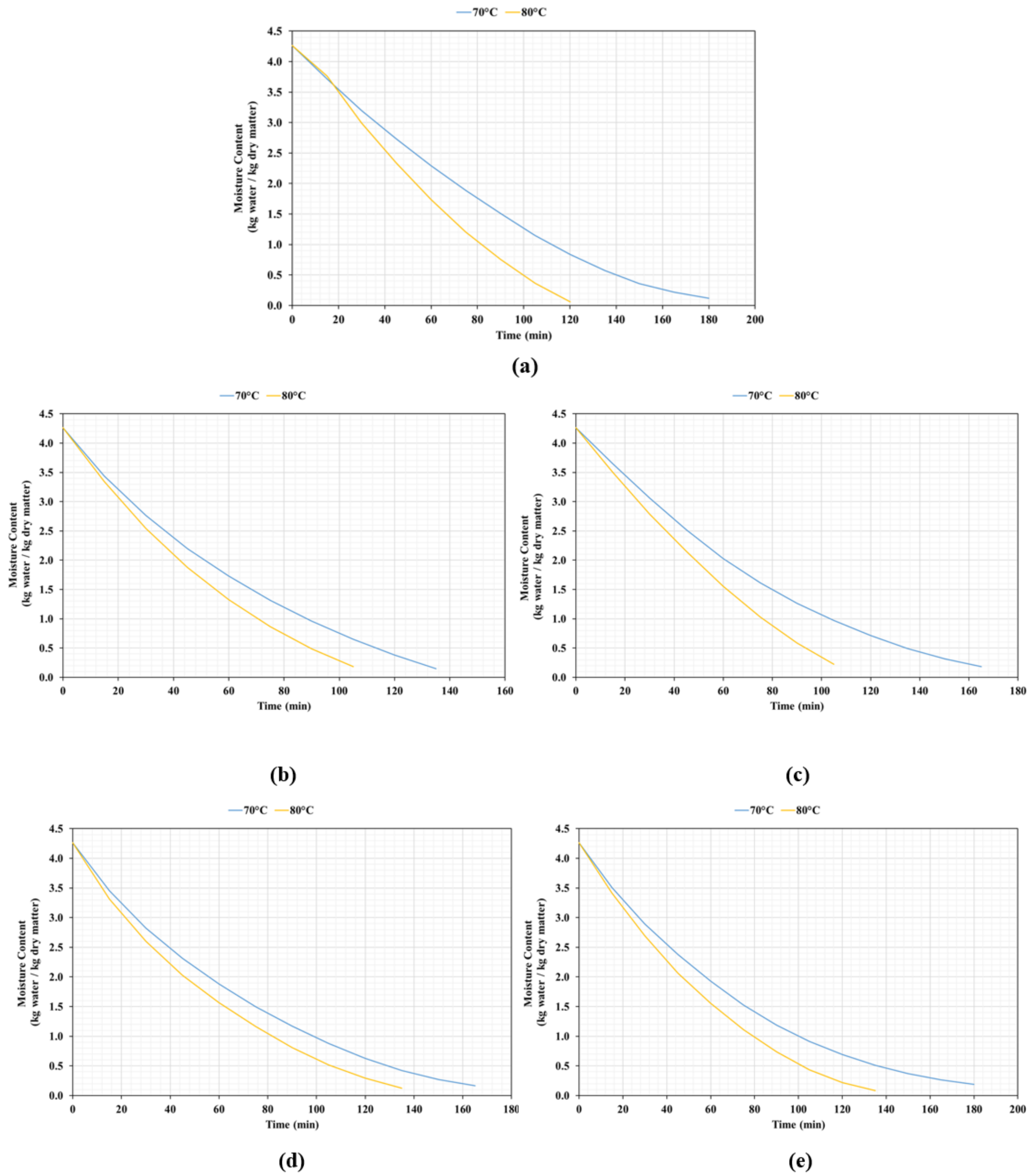

Fig. 2. The change in moisture content of blueberries for vacuum oven drying: (a) without any pretreatment, (b) 30°C, 1 min K_2CO_3 pretreatment, (c) 30°C, 3 min K_2CO_3 pretreatment, (d) 60°C, 1 min K_2CO_3 pretreatment, (e) 60°C, 3 min K_2CO_3 pretreatment

Fig. 2 presents the change of moisture content (M) with time for the 70°C and 80°C vacuum oven drying of blueberries without any pretreatment (Fig. 2a), pretreatment with 30°C K_2CO_3 solution (Fig. 2b and 2c) and pretreatment with 60°C K_2CO_3 solution (Fig. 2d and 2e). The results demonstrate that vacuum oven drying yielded much shorter drying times both for the untreated and K_2CO_3 pretreated blueberry samples. For instance, the drying times of the untreated blueberries were 180 min and 120 min for 70°C and 80°C drying temperatures respectively, when vacuum oven was employed. Moreover, the initial moisture content of 4.2632 kg water/kg dry matter was seen to decrease to 0.1184 and 0.0637 for the foresaid temperatures. The application of the chemical pretreatment showed a likewise tendency with the infrared drying experiments. When the blueberries were dipped in a 30°C K_2CO_3 solution for 1 min (Fig. 2b), the drying times were observed to similarly decrease to 135 and 105 min at 70°C and 80°C, respectively. Just like infrared drying, further contact time with K_2CO_3 solution did not cause a positive change in the drying times (Fig. 2c). For 30°C and 3 min K_2CO_3 pretreatment, the initial moisture content of 4.2632 kg water/kg dry matter decreased to 0.2266 at 70°C and to 0.1844 at 80°C. When K_2CO_3 solution's temperature was increased from 30 to 60°C, again a significant change was not observed. For vacuum oven drying at 70°C, the drying durations increased from 165 min to 180 min, when the dipping time was raised from 1 min to 3 min. For vacuum oven drying at 80°C, on the other hand, the drying durations were 135 min for both pretreatment times (Figs. 2d and 2e).

As outlined in the Experimental, the effective moisture diffusivity (D_{eff}) values were determined according to Eqn. 5, derived from the slopes of ln(MR) *versus* drying time plots. The resulting D_{eff} values, alongside the drying times for all experimental conditions, are compiled in Table 2.

Table 2. Drying times and D_{eff} values for the drying of blueberries

		Infrared Drying		Vacuum Oven Drying	
Pretreatment Type	Drying Parameter	70°C	80°C	70°C	80°C
Without Pretreatment	Drying Time (min)	255	135	180	120
	D_{eff} (m^2/s)	$5.14 \cdot 10^{-10}$	$1.13 \cdot 10^{-9}$	$7.98 \cdot 10^{-10}$	$1.28 \cdot 10^{-9}$
1 min K_2CO_3 Pretreatment, 30°C	Drying Time (min)	210	105	135	105
	D_{eff} (m^2/s)	$6.51 \cdot 10^{-10}$	$1.54 \cdot 10^{-9}$	$9.47 \cdot 10^{-10}$	$1.33 \cdot 10^{-9}$
3 min K_2CO_3 Pretreatment, 30°C	Drying Time (min)	210	120	165	105
	D_{eff} (m^2/s)	$5.90 \cdot 10^{-10}$	$1.19 \cdot 10^{-9}$	$7.68 \cdot 10^{-10}$	$1.10 \cdot 10^{-9}$
1 min K_2CO_3 Pretreatment, 60°C	Drying Time (min)	225	105	165	135
	D_{eff} (m^2/s)	$5.27 \cdot 10^{-10}$	$1.24 \cdot 10^{-9}$	$7.33 \cdot 10^{-10}$	$1.02 \cdot 10^{-9}$
3 min K_2CO_3 Pretreatment, 60°C	Drying Time (min)	165	90	180	135
	D_{eff} (m^2/s)	$7.40 \cdot 10^{-10}$	$1.54 \cdot 10^{-9}$	$7.30 \cdot 10^{-10}$	$1.15 \cdot 10^{-9}$

As demonstrated in Table 2, D_{eff} values increased with increasing drying temperature and the use of vacuum oven drying. For infrared drying, K_2CO_3 pretreatment resulted in a minor increase in the D_{eff} values for both drying temperatures. For the chemical pretreatments at 30°C, increasing the contact time with K_2CO_3 solution decreased the effective moisture diffusivities. On the contrary, 60°C chemical pretreatment experiments showed an opposite trend, in which increasing the dipping duration resulted in an increase in the effective moisture diffusivities. The highest D_{eff} value, $1.54 \cdot 10^{-9}$ m^2/s, was obtained for the experiment conducted at 60°C K_2CO_3 pretreatment for 3 min, at 80°C infrared drying. For vacuum oven drying, which proved to yield shorter drying times and higher D_{eff} values at low drying temperatures, D_{eff} was seen to increase only for the experiments that included K_2CO_3 pretreatment at 30°C and 1 min dipping time. The highest D_{eff} value was encountered at 80°C vacuum oven drying, which was $1.33 \cdot 10^{-9}$ m^2/s; and it was obtained for the experiment conducted at 30°C K_2CO_3 pretreatment for 1 min. As mentioned in the Introduction, the literature studies investigating the effect of K_2CO_3 chemical pretreatment on the drying performance of food products is still scarce. Bingol *et al.* [24] studied the convective air drying of Thompson seedless grapes at 60°C, where the grapes were pretreated in a mixture of potassium carbonate and ethyl oleate solution for 1, 2 and 3 min. The authors also investigated the effect of various dipping solution temperatures varying between 30 and 60°C on the drying performance. Accordingly, the drying rate of grapes improved with the use of chemical pretreatment. In accordance with the results obtained in the present study, dipping the grapes at low solution temperatures yielded a faster drying rate than 50°C solution temperature for the same pretreatment time. Moreover, similar to the findings for vacuum oven drying here, at dipping temperatures of 50°C and 60°C, it was observed that various dipping durations had no significant effect on the drying times. This conclusion was obtained in another study, in which the drying of cape gooseberries was investigated by using K_2CO_3 – olive oil and NaOH – olive oil mixtures with various concentrations as a pretreatment [18]. The samples were dipped in the pretreatment solutions at 28°C for 20 and 60 min. It was seen that chemical pretreatments resulted in higher moisture losses. However, increasing the pretreatment time did not have a major influence neither on the final moisture contents nor on the effective moisture diffusivities of the cape gooseberry samples.

Yılmaz and Uyak [13] studied the effect of 13 different pretreatment solutions involving K_2CO_3 and $NaHCO_3$ solutions with various oils on the sun drying performance of raisins. The authors stated that dipping the raisins in pretreatment solutions accelerated the drying process. Doymaz [25] used a cabinet dryer for the drying of black grapes at 60°C, by using 5% K_2CO_3 and 0.5% olive oil solution as a chemical pretreatment. The author has stated that the use of K_2CO_3 pretreatment decreased the drying time from 65 h to 28 h; and increased the D_{eff} value from $3.82\cdot10^{-10}$ m²/s to $1.05\cdot10^{-9}$ m²/s when compared to the untreated samples. A similar finding was also reported in another study, in which the cabinet drying of seedless grapes was investigated at 55, 65 and 75°C [26]. The grapes were pretreated with a solution involving 4% K_2CO_3 and 1% olive oil at 20°C for 1 min. The authors reported that the chemically pretreated grape samples dried faster than the untreated ones and had greater effective moisture diffusivities.

- *Mathematical modeling.* The mathematical modeling results that were obtained for the infrared drying of blueberries, both with and without pretreatments, are shown in Table 3; whereas those for vacuum oven drying are demonstrated in Table 4. The tables show the results for the best 3 models having the highest R^2, the lowest χ^2 and lowest RMSE values among the 14 models that have been tested.

Table 3. Statistical data of the best 3 drying models obtained for infrared drying

Infrared Drying, No Pretreatment					
70°C Drying Temperature			80°C Drying Temperature		
Verma *et al.*	Alibas	Weibull	Aghbaslo *et al.*	Page	Weibull
a = 0.093338 k = 0.041708 g = 0.011790 R^2 = 0.999957 χ^2 = 0.000008 RMSE = 0.002632	a = 0.938908 k = 0.017065 n = 0.952105 b = -0.000215 g = 0.062626 R^2 = 0.999949 χ^2 = 0.000012 RMSE = 0.002868	a = 0.944711 b = 77.347850 R^2 = 0.999932 χ^2 = 0.000011 RMSE = 0.003088	k_1 = 0.014800 k_2 = -0.003359 R^2 = 0.999640 χ^2 = 0.000082 RMSE = 0.008179	k = 0.006868 n = 1.251731 R^2 = 0.999578 χ^2 = 0.000096 RMSE = 0.008861	a = 1.251728 b = 53.476658 R^2 = 0.999578 χ^2 = 0.000096 RMSE = 0.008861
Infrared Drying, 30°C and 1 min K_2CO_3 Pretreatment					
70°C Drying Temperature			80°C Drying Temperature		
Logarithmic	Aghbaslo *et al.*	Page	Logarithmic	Aghbaslo *et al.*	Page
a = 1.024398 k = 0.013269 c = -0.027156 R^2 = 0.999968 χ^2 = 0.000006 RMSE = 0.002174	k_1 = 0.013438 k_2 = -0.000530 R^2 = 0.999908 χ^2 = 0.000015 RMSE = 0.003677	k = 0.012101 n = 1.035576 R^2 = 0.999788 χ^2 = 0.000035 RMSE = 0.005586	a = 1.108394 k = 0.020326 c = -0.114802 R^2 = 0.999796 χ^2 = 0.000042 RMSE = 0.005506	k_1 = 0.021623 k_2 = -0.003058 R^2 = 0.999136 χ^2 = 0.000157 RMSE = 0.011336	k = 0.015880 n = 1.126723 R^2 = 0.998096 χ^2 = 0.000346 RMSE = 0.016823
Infrared Drying, 30°C and 3 min K_2CO_3 Pretreatment					
70°C Drying Temperature			80°C Drying Temperature		
Midilli & Kucuk	Verma *et al.*	Two Term Exp.	Midilli & Kucuk	Logarithmic	Page
a = 1.000284 k = 0.023122 n = 0.861844 b = -0.000261 R^2 = 0.999956 χ^2 = 0.000008 RMSE = 0.002452	a = 0.049963 k = 0.176415 g = 0.012933 R^2 = 0.999573 χ^2 = 0.000070 RMSE = 0.007599	a = 0.047820 k = 0.270956 R^2 = 0.999571 χ^2 = 0.000076 RMSE = 0.007620	a = 0.998779 k = 0.021765 n = 0.978232 b = -0.000596 R^2 = 0.999890 χ^2 = 0.000028 RMSE = 0.004183	a = 1.081951 k = 0.018775 c = -0.086514 R^2 = 0.999872 χ^2 = 0.000028 RMSE = 0.004507	k = 0.015013 n = 1.103146 R^2 = 0.998895 χ^2 = 0.000214 RMSE = 0.013226
Infrared Drying, 60°C and 1 min K_2CO_3 Pretreatment					
70°C Drying Temperature			80°C Drying Temperature		
Verma *et al.*	Two Term Exp.	Alibas	Aghbaslo *et al.*	Two Term Exp.	Henderson&Pabis
a = 0.142754 k = 0.083827 g = 0.012060 R^2 = 0.999988 χ^2 = 0.000002 RMSE = 0.001277	a = 0.142377 k = 0.084725 R^2 = 0.999988 χ^2 = 0.000002 RMSE = 0.001281	a = 1.184367 k = 0.027807 n = 0.794394 b = 0.000385 g = -0.183970 R^2 = 0.999983 χ^2 = 0.000003 RMSE = 0.001501	k_1 = 0.024843 k_2 = -0.000796 R^2 = 0.998870 χ^2 = 0.000190 RMSE = 0.012481	a = 0.015305 k = 1.669035 R^2 = 0.998747 χ^2 = 0.000271 RMSE = 0.013142	a = 0.996844 k = 0.025856 R^2 = 0.998715 χ^2 = 0.000216 RMSE = 0.013309

Table 3. Continued

Infrared Drying, 60°C and 3 min K_2CO_3 Pretreatment					
70°C Drying Temperature			80°C Drying Temperature		
Aghbaslo *et al.*	Logarithmic	Parabolic	Alibas	Parabolic	Wang & Singh
k_1 = 0.020717 k_2 = 0.001650 R^2 = 0.998654 χ^2 = 0.000168 RMSE = 0.012181	a = 0.951661 k = 0.019081 c = 0.024022 R^2 = 0.998339 χ^2 = 0.000222 RMSE = 0.013533	a = 0.914913 b = -0.011803 c = 0.000041 R^2 = 0.989896 χ^2 = 0.001347 RMSE = 0.033306	a = 0.588739 k = 0.774614 n = 0.000002 b = -0.007907 g = 0.411261 R^2 = 0.989248 χ^2 = 0.002572 RMSE = 0.037455	a = 0.969178 b = -0.021311 c = 0.000124 R^2 = 0.997028 χ^2 = 0.000535 RMSE = 0.019729	a = -0.022563 b = 0.000134 R^2 = 0.996161 χ^2 = 0.000614 RMSE = 0.022419

Table 4. Statistical data of the best 3 drying models obtained for vacuum oven drying

Vacuum Oven Drying, No Pretreatment					
70°C Drying Temperature			80°C Drying Temperature		
Aghbaslo *et al.*	Parabolic	Wang & Singh	Midilli & Kucuk	Aghbaslo *et al.*	Parabolic
k_1 = 0.008337 k_2 = -0.003221 R^2 = 0.999921 χ^2 = 0.000013 RMSE = 0.003438	a = 1.005056 b = -0.009082 c = 0.000020 R^2 = 0.999832 χ^2 = 0.000031 RMSE = 0.005022	a = -0.008974 b = 0.000019 R^2 = 0.999812 χ^2 = 0.000032 RMSE = 0.005304	a = 1.003165 k = 0.003276 n = 1.327302 b = -0.001140 R^2 = 0.999912 χ^2 = 0.000025 RMSE = 0.003982	k_1 = 0.009662 k_2 = -0.005698 R^2 = 0.999365 χ^2 = 0.000140 RMSE = 0.010688	a = 1.025114 b = -0.011921 c = 0.000029 R^2 = 0.999053 χ^2 = 0.000234 RMSE = 0.013049
Vacuum Oven Drying, 30°C and 1 min K_2CO_3 Pretreatment					
70°C Drying Temperature			80°C Drying Temperature		
Verma *et al.*	Logarithmic	Parabolic	Midilli & Kucuk	Verma *et al.*	Logarithmic
a = 1.048215 k = 0.012915 g = -0.008318 R^2 = 0.999984 χ^2 = 0.000002 RMSE = 0.001305	a = 1.255558 k = 0.010626 c = -0.260330 R^2 = 0.999938 χ^2 = 0.000008 RMSE = 0.002594	a = 0.982561 b = -0.011741 c = 0.000036 R^2 = 0.999400 χ^2 = 0.000079 RMSE = 0.008082	a = 0.999890 k = 0.012547 n = 1.052367 b = -0.001376 R^2 = 0.999997 χ^2 = 0.000001 RMSE = 0.000667	a = -0.935529 k = 0.003666 g = 0.009988 R^2 = 0.999990 χ^2 = 0.000002 RMSE = 0.001208	a = 1.338851 k = 0.012065 c = -0.336694 R^2 = 0.999983 χ^2 = 0.000003 RMSE = 0.001579
Vacuum Oven Drying, 30°C and 3 min K_2CO_3 Pretreatment					
70°C Drying Temperature			80°C Drying Temperature		
Aghbaslo *et al.*	Parabolic	Wang & Singh	Parabolic	Wang & Singh	Midilli & Kucuk
k_1 = 0.010245 k_2 = -0.002686 R^2 = 0.999943 χ^2 = 0.000009 RMSE = 0.002741	a = 0.999894 b = -0.010258 c = 0.000027 R^2 = 0.999906 χ^2 = 0.000015 RMSE = 0.003517	a = -0.010261 b = 0.000027 R^2 = 0.999906 χ^2 = 0.000014 RMSE = 0.003518	a = 1.001804 b = -0.012653 c = 0.000034 R^2 = 0.999978 χ^2 = 0.000004 RMSE = 0.001764	a = -0.012589 b = 0.000034 R^2 = 0.999975 χ^2 = 0.000004 RMSE = 0.001879	a = 0.998960 k = 0.007904 n = 1.101464 b = -0.002040 R^2 = 0.999958 χ^2 = 0.000009 RMSE = 0.002445
Vacuum Oven Drying, 60°C and 1 min K_2CO_3 Pretreatment					
70°C Drying Temperature			80°C Drying Temperature		
Logarithmic	Aghbaslo *et al.*	Parabolic	Midilli & Kucuk	Logarithmic	Aghbaslo *et al.*
a = 1.140042 k = 0.011179 c = -0.146612 R^2 = 0.999859 χ^2 = 0.000021 RMSE = 0.004207	k_1 = 0.012230 k_2 = -0.001967 R^2 = 0.999434 χ^2 = 0.000081 RMSE = 0.008436	a = 0.972749 b = -0.010591 c = 0.000030 R^2 = 0.999066 χ^2 = 0.000143 RMSE = 0.010837	a = 0.999198 k = 0.017115 n = 0.958669 b = -0.000950 R^2 = 0.999931 χ^2 = 0.000019 RMSE = 0.003443	a = 1.164516 k = 0.013054 c = -0.171182 R^2 = 0.999859 χ^2 = 0.000033 RMSE = 0.004901	k_1 = 0.014517 k_2 = -0.002630 R^2 = 0.999227 χ^2 = 0.000161 RMSE = 0.011484
Vacuum Oven Drying, 60°C and 3 min K_2CO_3 Pretreatment					
70°C Drying Temperature			80°C Drying Temperature		
Midilli & Kucuk	Verma *et al.*	Two-Term Exp.	Logarithmic	Two-Term Exp.	Midilli & Kucuk
a = 1.000000 k = 0.262958 n = 0.000001 b = -0.004603 R^2 = 0.977569 χ^2 = 0.003958 RMSE = 0.055016	a = 0.476031 k = 0.014265 g = 0.014265 R^2 = 0.996863 χ^2 = 0.000519 RMSE = 0.020676	a = 0.003136 k = 4.521424 R^2 = 0.996728 χ^2 = 0.000583 RMSE = 0.021112	a = 1.235259 k = 0.012256 c = -0.229720 R^2 = 0.999790 χ^2 = 0.000053 RMSE = 0.006203	a = 0.002874 k = 6.267741 R^2 = 0.990913 χ^2 = 0.002606 RMSE = 0.040722	a = 1.000000 k = 0.215135 n = 0.000001 b = -0.006473 R^2 = 0.986249 χ^2 = 0.003934 RMSE = 0.050036

CONCLUSION

This study explored the impact of chemical pretreatment using a K_2CO_3 solution on the infrared and vacuum oven drying of blueberries. The research investigated how various drying methods, temperatures, pretreatment solution temperatures and pretreatment durations influenced the drying efficiency. Additionally, 14 drying models from existing literature were applied to mathematically model the drying process of blueberries. Vacuum oven drying was observed to reduce drying times, and drying rates were found to increase as the drying temperature was raised from 70 to 80°C. K_2CO_3 pretreatment solution's temperature was selected as 30°C and 60°C, and at both temperatures, the blueberry samples were dipped in the pretreatment solution for 1 min and 3 min. Accordingly, for the infrared drying experiments, it was seen that 1 min dipping of the blueberries in a 30°C K_2CO_3 pretreatment solution caused a decrease in the drying time and an increase in the D_{eff} values. However, further contact of the blueberries at the foresaid solution temperature, and increasing the solution temperature at this dipping time did not cause any significant change in the drying performance. 3 min pretreatment with 60°C K_2CO_3 solution yielded the highest D_{eff} value and the shortest drying time. The drying duration was between 135 - 255 min for the untreated blueberries, 105 – 210 min for blueberries treated with K_2CO_3 at 30°C, and 90 – 225 min for blueberries treated with K_2CO_3 at 60°C. D_{eff} values were found between $1.13 \cdot 10^{-9}$ – $5.14 \cdot 10^{-10}$ m^2/s for the untreated blueberries, $1.54 \cdot 10^{-9}$ – $6.51 \cdot 10^{-10}$ m^2/s for blueberries treated with K_2CO_3 at 30°C, and $1.54 \cdot 10^{-9}$ – $7.40 \cdot 10^{-10}$ m^2/s for blueberries treated with K_2CO_3 at 60°C.

When using vacuum oven drying, a comparable reduction in drying time and an increase in D_{eff} were observed after immersing the blueberries for 1 min in a K_2CO_3 solution at 30°C. However, raising the temperature of the pretreatment solution or extending the contact time with K_2CO_3 did not notably improve the drying efficiency. The drying duration was between 120 – 180 min for the untreated blueberries, 105 – 165 min for blueberries treated with K_2CO_3 at 30°C, and 135 – 180 min for blueberries treated with K_2CO_3 at 60°C. D_{eff} values, on the other hand, varied between $1.28 \cdot 10^{-9}$ – $7.98 \cdot 10^{-10}$ m^2/s for the untreated blueberries, $1.33 \cdot 10^{-9}$ – $9.47 \cdot 10^{-10}$ m^2/s for blueberries treated with K_2CO_3 at 30°C, and $1.15 \cdot 10^{-9}$ – $7.33 \cdot 10^{-10}$ m^2/s for blueberries treated with K_2CO_3 at 60°C.

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