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Drying and quality characteristics of fresh and sugar-infused blueberries dried with infrared radiation heating

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Abstract

We evaluated the finished product quality and infrared (IR) drying characteristics of fresh and sugar-infused blueberries dried with a catalytic infrared (CIR) dryer. IR drying tests were conducted at four product temperatures (60, 70, 80, and 90 °C) to evaluate the drying rate and the color and texture of the finished product. Fresh blueberries dried with convective hot air drying at 60 °C were used as control for comparison. The experimental data of moisture changes during IR drying were modeled with eight different models, including Page, modified Page, Thompson, Newton, Wang and Singh, and Henderson and Pabis, and two models developed in this study. The Thompson model showed the best fit to all experimental data. The CIR drying produced firmer-texture products with much reduced drying time compared with hot air drying. For fresh blueberries, CIR drying conserved drying time by 44% at 60 °C. The effective moisture diffusivity ranged from 2.24×10^{-10} to 16.4×10^{-10} m^2/s and from 0.61×10^{-10} to 3.84×10^{-10} m^2/s for fresh and sugar-infused blueberries, respectively.

Keywords: Blueberries; Drying; Infrared radiation heating; Quality; Sugar infusion; Temperature

1. Introduction

Blueberries (*Vaccinium*) are largely consumed perishable fruits with high economic value and healthy nutrients. They are a rich source of antioxidants such as anthocyanins, which benefit human health and also have protective properties against diseases such as memory loss, cancer, heart disease, urinary disease, vision problems and aging (Kalea et al., 2006; Norton, Kalea, Harris, & Klimis-Zacas, 2005; Schmidt et al., 2004; Sweeney, Kalt, MacKinnon, Ashby, & Gottschall-Pass, 2002; Wu et al., 2004). North America is the world's leading blueberry producer, accounting for nearly 90% of world production. According to the United Nations Food & Agricultural Organization, more than 42,000 metric tons of blueberries are harvested each year (US Highbush Blueberry Council, 2007). About 50% of all blueberries produced are dedicated to the fresh market, with only 2–3 weeks of shelf life. In order to extend the availability of blueberries out of season, fresh blueberries are also subjected to drying directly or after sugar infusion. The products are usually served as snacks or food ingredients for bakeries, tea or capsules. Sucrose is a typical infusion agent for improved yield, flavor and texture quality of processed products.

Drying is one of the most common methods used for preserving blueberries and extending their shelf lives by reducing the moisture content to a low level. The typical moisture contents of finished products may depend on drying methods for

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different applications. They range from 11 to 18 g moisture/100 g wet weight [water activity (aw) = 0.5–0.6] for hot air drying, less than 40 g moisture/100 g wet weight (aw = 0.5–0.87) for osmotic dehydration, 0–2 g moisture/100 g wet weight (unsweetened) or 9–14 g moisture/100 g wet weight (sweetened) for freeze drying, and 3–5 g moisture/100 g wet weight for drum drying (USHBC, 2007). Among these methods, freeze drying is the most expensive and is mainly used in producing high value products when protection of functional components in blueberries is desired (Wood & Barker, 1964). Osmotic dehydration is widely used in blueberry processing because it removes large amounts of water from fruits without causing phase changes, loads the costly fruits with inexpensive sugar, and increases product weight. Hot air and drum drying methods may be used to dry fresh and osmotic dehydrated products to shelf-stable moisture content. Hot air drying has been extensively studied for drying fresh, frozen and sugar-infused blueberries. However, hot air drying takes prolonged time resulting in degradation of heat sensitive components and discoloration of the final product (Schmidt, Erdman, & Mary Ann Lila, 2005; Skrede, Wrolstad, & Durst, 2000).

Microwave and infrared (IR) drying have been studied for achieving fast drying and reducing quality loss of fruits and vegetables (Baysal, Icier, Ersus, & Yldz, 2004). A combination of hot air and microwave drying of osmotic dehydrated blueberries had similar or better product quality compared with freeze-dried products with much reduced drying time (Venkatachalapathy & Raghavan, 1998). Compared with hot air drying, IR heating offers many advantages such as greater energy efficiency, heat transfer rate, and heat flux, which results in reduced drying time and higher drying rate. It has been investigated as a potential method for increasing heating efficiency and obtaining high quality of dried foodstuffs, including peaches (Wang & Sheng, 2006), carrots (Togrul, 2006), onions (Wang, 2002), rice (Afzal & Abe, 1997), and many other fruits and vegetables (Volonchuck & Shornikova, 1998). However, we found no report on IR drying of blueberries in the literature.

Mathematical modeling of mass transfer is a very useful tool in investigating the intrinsic kinetics of a drying process. Empirical models can derive a direct relationship between moisture ratio (MR) and drying time. Various mathematical models have been proposed to describe the IR drying characteristics of many products, including onions (Jain & Pathare, 2004; PraveenKumar, Umesh, & Ramesh, 2006; Sharma, Verma, & Pathare, 2005; Wang, 2002), eggplants (Wang, 2002), and rice (Abe & Afzal, 1997; Hashimoto & Kameoka, 1999). Mathematical models are also available for thin layer air-drying of food products, such as plums (Goyal, Kingsly, Manikantan, & Ilyas, 2007), bananas (Baini & Langrish, 2007), kiwifruits (Sigmal, Femenia, Garau, & Rossello, 2004), figs (Babalis, Papanicolaou, Kyriakis, & Belessiotis, 2006), grapes (Doymaz, 2006), potatoes (Akpinar, 2006), and apricots (Bozkir, 2006). The models are usually semi-theoretical models with assumption of mass transfer obeying Fick's law (Parry, 1985).

Although several models have been used successfully to describe the thin layer drying behaviors of many food products, the suitability of these models to IR drying of blueberries is unknown (Eidt & Macarthur, 1944; MacGregor, 2005; Ramaswamy & Nsonzi, 1998). Therefore, the objectives of this study were (1) to investigate the drying and quality characteristics of fresh and sugar-infused blueberries under different temperatures using catalytic IR heating, and (2) to develop suitable mathematical models to describe the drying characteristics.

2. Materials and methods

2.1. Blueberries

Fresh blueberries (O'Neil, *Vaccinium*) used in this study had initial moisture content (MC) of 85 g moisture/100 g wet weight and weighted average diameter of 12 mm. The moisture content was measured by the method AACC Method 44-15A (Moisture – Air-Oven Methods) (AACC, 2000). The blueberries were obtained from a local market and stored in a refrigerator at 4 ± 1 °C before IR drying. Individual quick frozen (IQF) blueberries of the Patriot variety with weighted average diameter of 14 mm and MC of 85 g moisture/100 g wet weight were obtained from Gladwin Farms, Ltd (Abbotsford BC, Canada) for the tests of infused blueberries. The frozen blueberries were thawed at 4 °C overnight, warmed up at room temperature for 2 h, and blotted with tissue paper to remove free water on the surface before sugar infusion. The infusion process was conducted using a solution-circulation system (Fig. 1, see description of the system in Section 2.2) with 60 °Brix sucrose solution at ambient temperature (23–25 °C) for 10 h. The weighted average diameter of infused blueberries was reduced to 10 mm because of shrinkage during the infusion. Infused blueberries were removed from

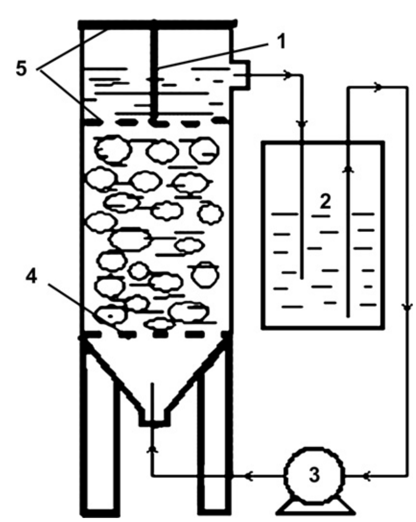

Fig. 1. Schematic of circling infusion system: 1, infusion container; 2, storage container of infusion medium; 3, pump; 4, metal screen; 5, cover.

the infusion system, rinsed quickly with tap water, blotted with paper towels to remove free water on the surface of blueberries, and stored at 4 ± 1 °C for drying tests. The MC of infused blueberries was 47 g moisture/100 g wet weight [corresponding to water activity (aw) of 0.882]. The water activity was measured by AquaLab Water Activity Meter Series 3TE (Decagon Devices, Inc. WA, USA). The infused blueberries were kept in a zipped plastic bag at ambient temperature overnight to reach equilibrium temperature before IR drying tests.

2.2. Infusion equipment setup

The infusion system (Fig. 1) consisted of a cylindrical infusion tank (10 cm in diameter, 35 cm in height) with a cone-shaped bottom (7.5 cm in height), an inlet at the bottom of the tank, and an outlet (1.0 cm in diameter) located at 6.5 cm below the top of tank. Two metal screens were used to keep the blueberries in the infusion solution and only the solution circulated through a pump and tubes. The ratio of blueberries and solution was 1:5 in weight to volume. The concentration of sugar solution was kept at 60 ± 2 °Brix by adding concentrated sugar solution to the storage container of infusion media. The concentration of the sugar solution was measured using a digital Abbe refractometer AR2008 (Kruss, Hamburg, Germany) according to the method of AOAC 932.12.

2.3. IR dryer setup

The catalytic infrared (CIR) dryer used in this study consisted of two emitters (Catalytic Industrial Group Inc., Independence, KS, USA) and two aluminum boxes (65.5 × 37 × 44 cm) used to improve the uniformity of IR distribution (Fig. 2). The blueberries were placed on a metal screen drying tray (65.5 × 37 cm) located 47 cm from the upper emitter and 55 cm from the lower emitter. The average IR intensity was 4000 W/m^2 as measured by an Ophir FL205A Thermal Excimer Absorber Head (Ophir Optronics Inc., Wilmington, MA, USA). During drying tests, the temperature of blueberries was controlled by adjusting natural gas input through a gas valve controlled by a computer system.

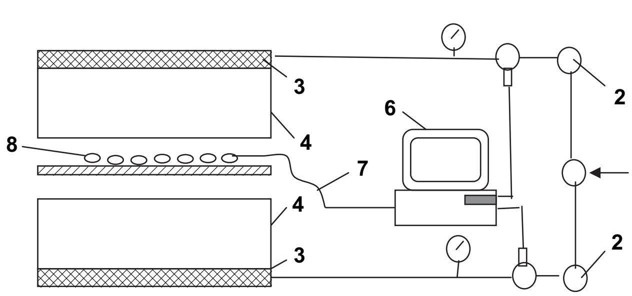

Fig. 2. Schematic of IR drying equipment: 1, natural gas supply; 2, gas flow control; 3, emitter; 4, aluminum box; 5, drying tray; 6, computer control system; 7, thermocouples; 8, blueberry sample.

Temperature was measured by placing type T thermocouples (response time 0.15 s) underneath the skin of blueberries. Gabel, Pan, Amaratunga, Harris, and Thompson (2006) provided a more detailed description of the CIR system.

2.4. Drying trials

Four drying temperatures (60, 70, 80 and 90 °C) were tested for both fresh and sugar-infused blueberries. In each drying test, 10–15 small metal wire containers (6 cm in diameter) each containing 10–15 g blueberries were placed on the drying tray. The corresponding average loading was 3.6–5.4 kg/m^2. During the drying course, one container was removed at a specific time and used for measuring weight loss. The targeted water activity of dried products was 0.6, the general level limits for the growth of molds, yeasts, and bacteria. At this point, the final weight losses were 80% for fresh blueberries (MC = 18 g moisture/100 g wet weight) and 30% for sugar-infused blueberries (MC = 23 g moisture/100 g wet weight). These dried samples were considered final products with aw of 0.6. For comparison, fresh blueberries were also dried using the Proctor & Schwartz Cabinet Dryer (Proctor & Schwartz Ltd, Glasgow, UK) at air temperature of 60 °C and air speed of 4 m/s. All experiments were replicated three times at each temperature and averages of weight loss and MC were reported.

2.5. Determination of drying rate and diffusion coefficient

The overall drying rate (DR) (Kar & Gupta, 2003) was calculated using the equation

$$\mathrm{DR} = \frac{M_0 - M_t}{t} \quad (1)$$

where DR is overall drying rate (g water/g dry solid min^{-1}); M_0 is moisture content of blueberries at time 0 (g water/g dry solid); and M_t is moisture content of blueberries at time t (g water/g dry solid).

The moisture ratio (MR) of samples was calculated using the equation

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

where M_e is equilibrium moisture content of sample (g water/g dry solid). The value of M_e is relatively small compared with M_t or M_0, especially for IR drying (Diamante & Munro, 1993). Therefore, M_e was assumed to be zero in this study.

The effective moisture diffusivity of blueberries was calculated using Crank's equation (1975), assuming the shape of blueberries as spherical with negligible shrinkage and that moisture migration was due to diffusion with a constant temperature and diffusion coefficient (El-Beltagy, Gamea, & Amer Essa, 2007). The equation is given as

$$\mathrm{MR} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}e^{\left(\frac{-n^2\pi^2 D_e t}{r^2}\right)} \tag{3}$$

where D_e is moisture diffusivity (m^2/s), r is the radius of the blueberries (m), and t is time (s). For long drying durations, Eq. (3) can be simplified to an equation in the form

$$\ln(\mathrm{MR}) = \ln\frac{6}{\pi^2} - \frac{\pi^2 D_e t}{r^2} \tag{4}$$

Then the effective moisture diffusivity D_e can be calculated using the equation

$$D_e = \frac{-0.101\ \ln(\mathrm{MR}) - 0.0504}{(t/r^2)} \tag{5}$$

The effective moisture diffusivity D_e was calculated at each corresponding moisture content and time in this study. The average effective moisture diffusivity $D_{e,\,avg}$ was calculated from positive D_e obtained using the data for all effective moisture diffusivity (Singh & Gupta, 2007) as

$$D_{avg} = \frac{\sum_1^n D_e}{n} \tag{6}$$

Activation energy was also calculated by using the Arrhenius relation (Singh & Gupta, 2007), which is presented as

$$D_{e,avg} = D_0 e^{-\left(\frac{E_a}{R(T+273)}\right)} \tag{7}$$

where T is temperature (°C); R is gas constant having a constant value of 8.314×10^{-3} kJ/mol K^{-1}; D_0 is effective moisture diffusivity at 273 K temperature; and E_a is activation energy (kJ/mol). E_a/R was obtained as the slope of the straight line of nature log of $D_{e,avg}$ vs. $1/(T+273)$.

2.6. Mathematical modeling of drying curve

Six mathematical models successfully used in other research studies were used to evaluate the relationship between moisture ratio and drying time (drying curve) of fresh and sugar-infused blueberries (Table 1). The experimental data were also fitted with other regression equations; two of them with a high degree of fitting are also reported in this study. The model constants were estimated using SPSS14.0 software (SPSS Inc., Chicago, IL, USA) according to the nonlinear modeling procedure. Three parameters, coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE) were used to evaluate the fit of tested models to the experimental data (Diamante & Munro, 1993; Karim & Hawlader, 2005; Meeso, Nathakaranakule, Madhiyanon & Soponronnarit, 2007; Sharma et al., 2005; Togrul, 2006; Wang, Sun, Chen, Liao & Hu, 2007). Analysis of variance (ANOVA) of fitness parameters among the different models was conducted using the Duncan method at $p < 0.05$. The model used for describing the drying characteristics of blueberries under IR radiation heating had the lowest χ^2 and RMSE values and the highest R^2 value (Togrul, 2006). Statistical values were defined with equations

Table 1
Mathematical models of single-layer blueberry drying

Code of model	Model equation	Model name
1	$\mathrm{MR} = a\exp(-kt)$	Henderson and Pabis (Henderson & Pabis, 1961)
2	$\mathrm{MR} = at^2 + bt + 1$	Wang and Singh (Wang & Singh, 1978)
3	$\mathrm{MR} = \exp(-kt)$	Newton (Ayensu, 1997)
4	$\mathrm{MR} = \exp(-kt^n)$	Page (PraveenKumar et al., 2006; Doymaz, 2007)
5	$\mathrm{MR} = \exp[-(kt)^n]$	Modified Page (Togrul, 2005; Vega, Fito, Andres, & Lemus, 2007)
6	$t = a[\ln(\mathrm{MR})]^2 + b\ln(\mathrm{MR})$	Thompson (Thompson et al., 1968)
7	$\mathrm{MR} = \exp[-(at^2 + bt)]$	Regression model
8	$t = a\mathrm{MR}^2 + b\mathrm{MR} + c$	Regression model

$$R^2 = 1 - \frac{\sum_1^n \left(\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2}{\sum_1^n \left(\overline{\mathrm{MR}_{\exp}} - \mathrm{MR}_{\mathrm{pre},i}\right)^2} \tag{8}$$

$$\chi^2 = \frac{\sum_{i=1}^N \left(\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2}{N-n} \tag{9}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^N \left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\exp,i}\right)^2}{N}} \tag{10}$$

where $\mathrm{MR}_{\exp,i}$ and $\mathrm{MR}_{\mathrm{pre},i}$ are experimental and predicted moisture ratios, respectively; $\overline{\mathrm{MR}_{\exp}}$ is the average of experimental moisture ratio; N is the number of observations, and n is the number of drying constants.

2.7. Quality analysis of dried blueberries

The color and texture quality of dried blueberries were measured with a colorimeter (Minolta CR-200, Japan) and a Texture Analyzer TA.XT2i (Stable Micro Systems, Ltd., Surrey, UK).

Changes in the individual color parameters of blueberries before and after drying were calculated as

$$\Delta L = L - L_0, \Delta a = a - a_0, \Delta b = b - b_0 \tag{11}$$

$+a$ is redness, $-a$ is greenness, $+b$ is yellowness, and $-b$ is blueness (Minolta, 1999). In Eq. (11), L_0, a_0 and b_0 are the color values for fresh blueberries, while L, a and b are the color values in dried blueberries.

The subscript 0 refers to the color of fresh blueberries before drying, while L, a and b are color values after drying. The total color difference (ΔE) was then determined using the following equation (Nsonzi & Ramaswamy, 1998):

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \tag{12}$$

Texture quality was evaluated by measuring the hardness, springiness, cohesiveness, and chewiness of samples using TPA mode under the following instrument parameters: pre test speed, 2 mm/s; test speed, 1 mm/s; post test speed, 1 mm/s; time lag between two compressions, 1 s; strain, 50% of sample height; trigger force, 20 g; data acquisition rate, 200 pps; 2 mm diameter cylinder probe. The texture parameters were obtained from the software provided by the manufacturer of the texture analyzer (Texture Technologies, 2007). Analysis of variance (ANOVA) of quality parameters among the different samples was conducted using the Duncan method at $p < 0.05$ level.

2.8. Scanning electron microscopy

The microstructures of fresh blueberries and the blueberries dried for 60 min with IR at 70 °C were studied using scanning electron microscopy. The samples were prepared by placing them in a fixative consisting of 2.5% glutaraldehyde and 2% formaldehyde in 0.1 M sodium cacodylate buffer, pH 5.0, in open vials in a vacuum oven without heat. The vacuum was closed and opened over a period of 5 min to remove air from the samples and allow penetration of the fixative. Sample vials were capped and the samples were fixed overnight at 4 °C. Then the samples were cut into smaller pieces and put into fresh fixative overnight at 4 °C. The samples were rinsed in two exchanges of 0.1 mol/L sodium cacodylate buffer, pH 5.0, 20 min per exchange, and dehydrated three times in a graded series of ethanol (30, 50, 70, 95 and100%) for 30 min per step. A sub-set of the samples was cryofractured in liquid nitrogen. Cryofracturing consisted of removing samples from the final 100% ethanol and plunging directly into liquid nitrogen held in a styrofoam container with a metal plate in the bottom. The samples were fractured while under liquid nitrogen with a liquid nitrogen-chilled razor blade held with a vise grip. The fractured, frozen samples were picked out of the liquid nitrogen with a chilled tweezers and placed back into 100% ethanol to thaw.

All samples were critical point dried in a Tousimis 815 Autosamdri Critical Point Dryer (Tousimis, Rockville, MD). Samples were mounted onto aluminum specimen stubs using a mixture of two-component ‘‘extra-time’’ epoxy (Loctite Brand, Henkle Technologies, Düsseldorf, Germany) and water-based conductive graphite adhesive (Electron Microscopy Sciences, Hatfield, PA, USA). The mixture was approximately equal parts hardener, resin and graphite. After drying overnight in a desiccator, the samples were coated with gold–palladium in a Desk II sputter coating unit (Denton Vacuum, Moorestown, NJ, USA) and viewed at 2 kV in a Hitachi S-4700 scanning electron microscope (Hitachi Ltd., Tokyo, Japan).

3. Results and discussions

3.1. Effect of temperature on drying time and drying rate

The effect of temperature on moisture ratio change of fresh and sugar-infused blueberries at different times is shown in Fig. 3. Drying temperature significantly affected the moisture change of both fresh and sugar-infused blueberries. With increasing drying temperature in the tested range, the amount of moisture removed from blueberries increased and the time to achieve specific moisture content in finished products was reduced. However, when the drying temperature was increased from 80 to 90 °C, the increase of drying rate was less than that for a temperature of 60 to 80 °C. IR drying had much higher drying rate compared with the hot air drying. The required IR drying times for obtaining the final products were 540, 210, 120 and 90 min at 60, 70, 80 and 90 °C, respectively. These times corresponded savings in drying time of 44, 78, 88 and 91% compared with the hot air drying at 60 °C (960 min) (Fig. 4). For sugar-infused blueberries, the required IR drying times were 315, 120, 60 and 50 min at 60, 70, 80 and 90 °C, respectively, less than the required drying time of fresh blueberries. There were two possible reasons causing the reduced drying time of sugar-infused blueberries. One was that sugar-infused blueberries had low initial moisture content, 47 g moisture/100 g wet weight, which was much

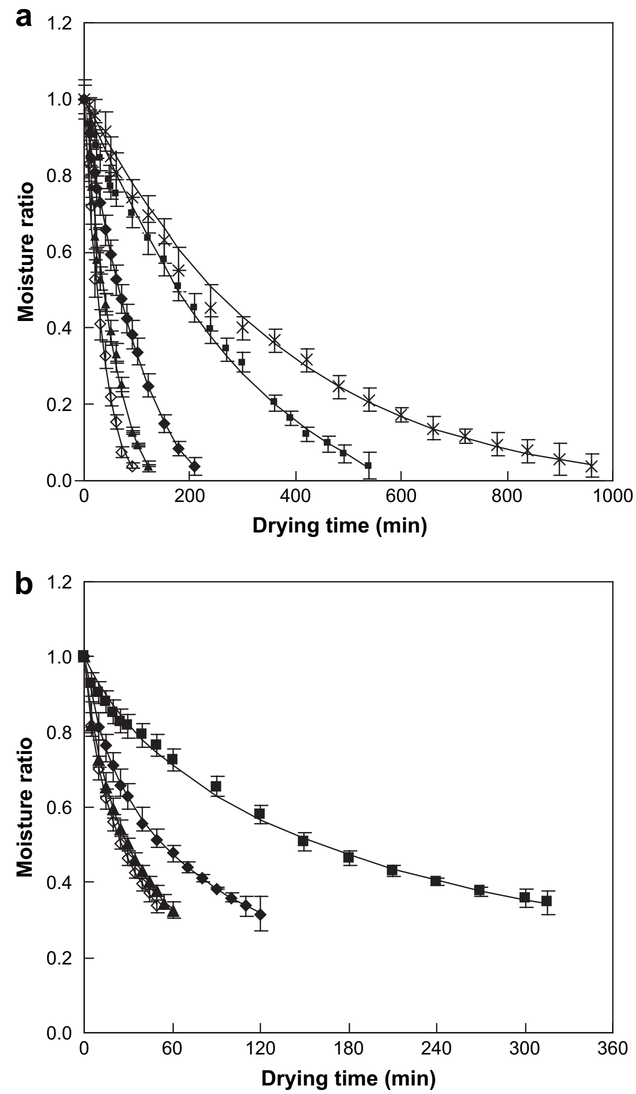

Fig. 3. Experimental and Thompson model predicted drying curves of fresh blueberries (a) and sugar-infused blueberries (b) under different drying conditions. *, hot air at 60 °C; ■, 60 °C, ◆, 70 °C, ▲, 80 °C, and ◇, 90 °C under infrared radiation; —, predicted data.

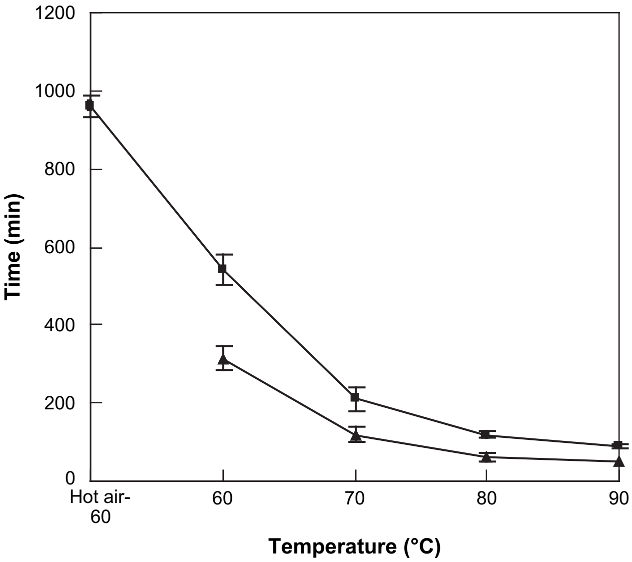

Fig. 4. Drying times for achieving dried blueberries with water activity of 0.63 under different drying temperatures. -■-, Fresh blueberries; -▲-, Sugar-infused blueberries.

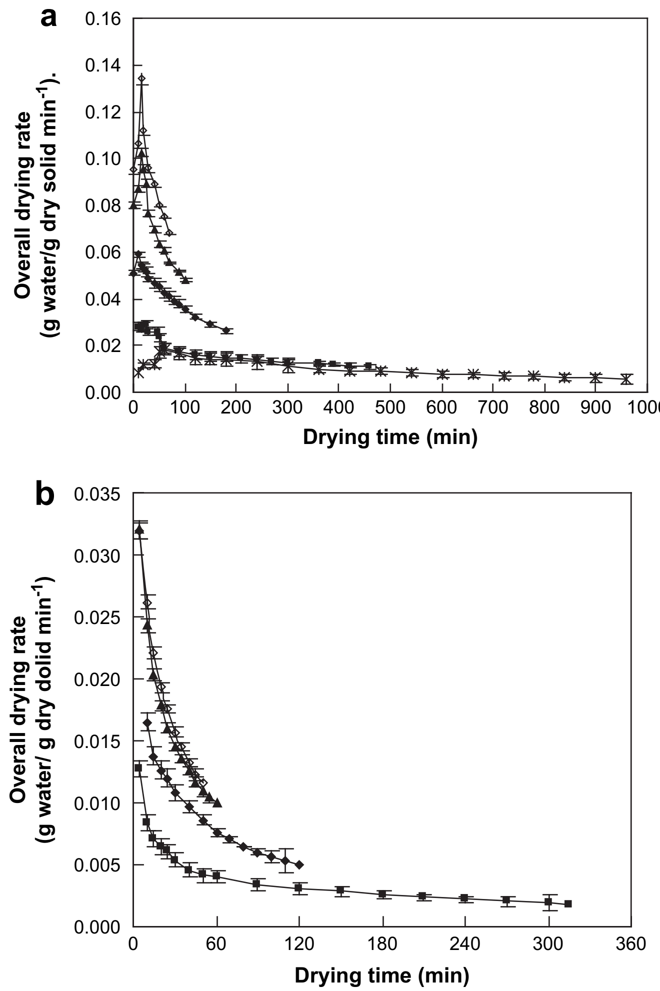

Fig. 5. Overall drying rate vs. drying time for fresh blueberries (a) and sugar-infused blueberries (b) under different drying temperatures. -✻-, hot air at 60 °C; -■-, 60 °C, -◆-, 70 °C, -▲-, 80 °C, and -◇-, 90 °C under infrared radiation.

lower than that in fresh blueberries, 85 g moisture/100 g wet weight. Another reason was that sugar-infused blueberries can be dried to slightly higher moisture to achieve a similar water activity compared to the dried fresh blueberries. Therefore, much less moisture needed to be removed during drying, which resulted in less required drying time compared to fresh berries.

This is because most water has been removed from the blueberries before drying and the water activity can be reduced to a lower level when there is sugar in the berries.

The overall drying rates vs. drying time or MC of both fresh and sugar-infused blueberries are shown in Figs. 5 and 6. Overall drying rates increased with the increase in drying temperature for both fresh and sugar-infused blueberries. No clear constant drying rate period was found at all drying conditions because the thin layer of product could not provide a constant supply of water during the drying period. This phenomenon agreed with the drying characteristics of many bioproducts under thin layer drying (Chua & Chou, 2005; Ibrahim, 2007; Sacilik, Keskin, & Elicin, 2006). However, a heating up stage was evident for fresh blueberries but not for sugar-infused blueberries. IR drying of sugar-infused blueberries occurred mainly during the falling rate period, which is similar to that of hot air drying of sugar-infused blueberries (Lewicki, 1998; Nicoleti, Telis-Romero, & Telis, 2001). Sugar-infused blueberries showed an absence of the heating up stage under all IR drying conditions because the moisture content in the samples was low and the drying process was governed mainly by moisture diffusion.

The increased drying rate during the heating up stage in fresh blueberries could be attributed to increased evaporation of water both on the surface of and in the blueberries due to increasing temperatures (Chua & Chou, 2005). As the drying process continues, less free water on the berry surface is available and then the drying rate could be dominated by the moisture diffusion from the inside to the surface of berries. Therefore, the drying rate starts to decrease and the falling rate period begins, which often happens in the later drying stage for many agricultural products. The time needed for the heating up period depends on the energy supplied. In this study, the time was 30 and 15 min for fresh blueberries at 60 and 90 °C, respectively, and 40 min under convectional air-drying at 60 °C.

The IR drying rate of fresh blueberries was much higher – almost 10 times – than that of sugar-infused blueberries at a similar moisture range under all drying conditions. At 60–90 °C, for example, the drying rate of fresh blueberries was in the range of 0.01–0.08 g water/g dry solid min^{-1} at a moisture content of 0.5 g water/g dry solid, but the corresponding drying rate of sugar-infused blueberries was only 0.003–0.01 g water/g dry solid min^{-1} (Fig. 6).

The reduction in drying rate for sugar-infused blueberries compared with that for fresh blueberries may be attributed to the inhibition of moisture diffusion by sugar infused to the fruits. The sugar infused in fruits might form a barrier to

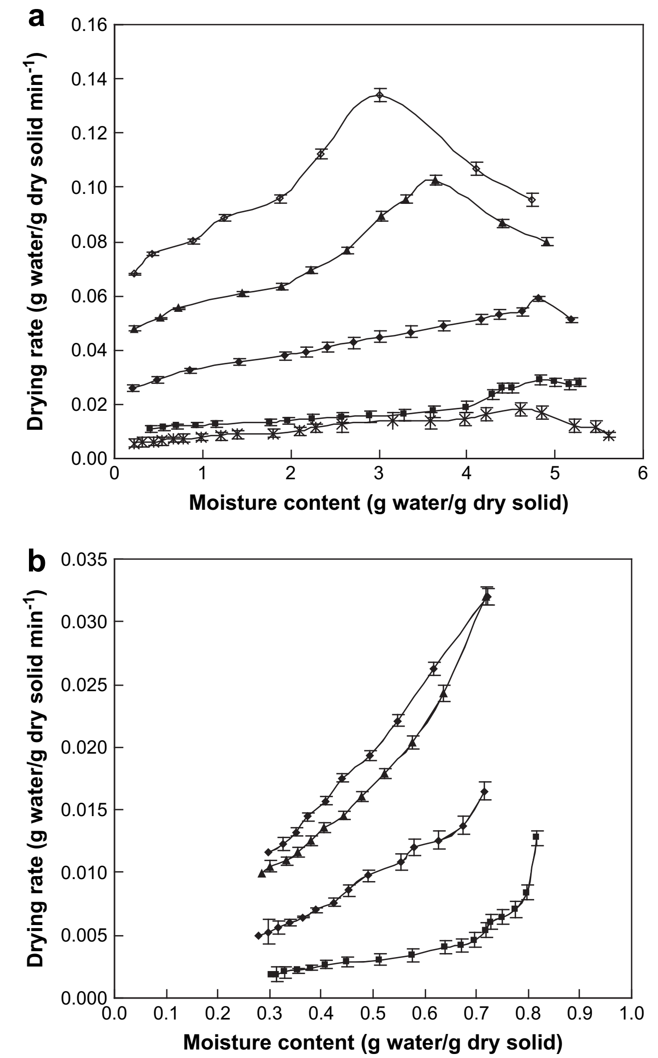

Fig. 6. Overall drying rate vs. moisture content for fresh blueberries (a) and sugar-infused blueberries (b) at different drying temperatures. -✻-, hot air at 60 °C; -■-, 60 °C, -◆-, 70 °C, -▲-, 80 °C, and -◇-, 90 °C under infrared radiation.

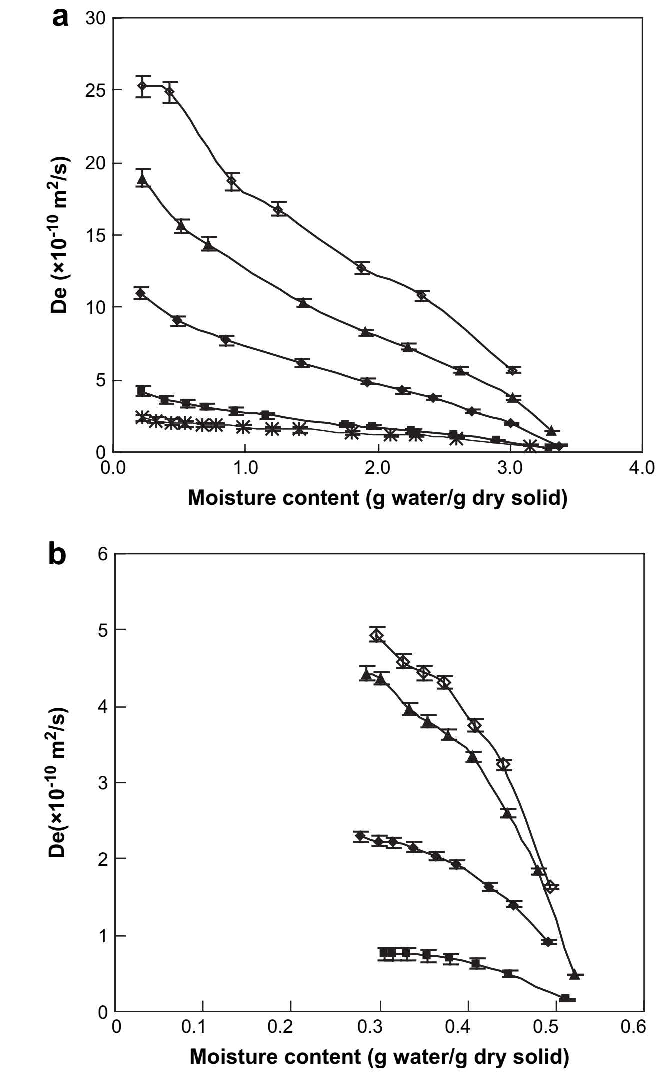

Fig. 7. Moisture diffusivity vs. moisture content for fresh blueberries (a) and sugar-infused blueberries (b) at different drying temperatures. -✻-, hot air at 60 °C; -■-, 60 °C, -◆-, 70 °C, -▲-, 80 °C, and -◇-, 90 °C under infrared radiation.

the movement of water during the drying period because it has higher stickiness and lower moisture diffusivity than water which dominates in fresh blueberries. The inhibition of sugar in infused blueberries to the moisture diffusion was also validated by the lower D_0 for sugar-infused blueberries (0.31×10^{-11} m^2/s) compared with fresh blueberries (5.89×10^{-11} m^2/s).

The high drying rate at high drying temperature could be due to more heating energy which speeds up the movement of water molecules and results in higher moisture diffusivity. The effective moisture diffusivities at different moisture contents are shown in Fig. 7 and the average moisture diffusivities ($D_{e,avg}$) are summarized in Table 2 for IR drying of fresh blueberries and sugar-infused blueberries. When drying temperature increased from 60 to 90 °C, $D_{e,avg}$ increased from 2.24×10^{-10} to 16.4×10^{-10} m^2/s for fresh blueberries and from 0.61×10^{-10} to 3.84×10^{-10} m^2/s for sugar-infused blueberries. For fresh blueberries under the same drying temperature (60 °C), the $D_{e,avg}$ of IR drying (2.24×10^{-10} m^2/s) was higher than that of hot-air drying (1.58×10^{-10} m^2/s). The high moisture diffusivity at high drying temperature agrees with that in convectional air-drying of fresh plum and osmotic dehydrated carrots (Goyal et al., 2007; Singh & Gupta, 2007).

The increase of D_e in the later drying stage may be attributed to the changes in the internal structure during the drying course. The D_e increased by nearly 10 times for fresh blueberries and two times for sugar-infused blueberries at

Table 2
Average moisture diffusivities of fresh and sugar-infused blueberries under different drying conditions ($\times 10^{-10}$ m^2/s)

Fresh blueberries	Average moisture diffusivity ($D_{e,avg}$)	Sugar-infused blueberries	Average moisture diffusivity ($D_{e,avg}$)
Hot air-60 °C	1.58		
IR-60 °C	2.24	IR-60 °C	0.61
IR-70 °C	5.19	IR-70 °C	1.87
IR-80 °C	9.52	IR-80 °C	3.16
IR-90 °C	16.4	IR-90 °C	3.84

70 °C during the drying course. The average diameter decreased from 11 to 9 mm for fresh blueberries and from 10 to 9 mm for sugar-infused blueberries. Scanning electron microscopy (SEM) showed that the plasma membrane and cell wall of cells in fresh blueberries were intact before drying but were cracked in the later drying stage (Fig. 8). The inner tissue showed a loose and porous structure in the later drying stage, which would allow water to be transferred more easily from the inside to the surface of blueberries. Stojanovic and Silva (2006) reported that the tissue structure of sugar-infused blueberries changed less than in blueberries without sugar-infusion pretreatment under convective air-drying. The internal tissue of sugar-infused blueberries suffered small changes with reduced intercellular space and swollen dendritic formations, even at significantly reduced moisture level. The cells in sugar-infused blueberries were filled with sugar (Stojanovic & Silva, 2006). Therefore, more opened structure and greater decrease of diameter might contribute to the higher increase of D_e for fresh blueberries than sugar-infused blueberries. The higher effective moisture diffusivity at 273 K temperature (D_0) of fresh blueberries compared with that of sugar-infused blueberries also indicated that the sugar infused in blueberries had inhibitive effects on water transfer.

For IR drying, the activation energy (E_a) of fresh blueberries was 66.3 kJ/mol, slightly higher than that for sugar-infused blueberries (61.2 kJ/mol). This might be due primarily to the higher drying rate of fresh blueberries at high temperatures, especially when the temperature was increased from 80 to 90 °C, compared with that of sugar-infused blueberries. Activation energy (Arrhenius activation energy) is defined as an empirical parameter characterizing the exponential temperature dependence of the rate coefficient in the IUPAC Compendium of Chemical Terminology (2nd Edition, 1997). In chemistry and biology, activation energy is the threshold energy, or the energy that must be overcome in order for a chemical reaction to occur. At high temperature, the probability that two molecules will collide is high. The high collision rate results in a higher kinetic energy, which has an effect on activation energy of the reaction. Collision rate in fresh blueberries might be higher than that in sugar-infused blueberries since the sugar could inhibit the movement of water to some degree.

3.2. Modeling of drying process

The results of model fitting criteria showed that all models had good fitness to the experimental data under all drying conditions. For all models, the R^2, χ^2, and RMSE are higher than 0.94, lower than 0.03 and 0.05, respectively. To determine the overall fitness of each model for all drying temperatures, the average values of R^2, χ^2, and RMSE are calculated and reported in Table 3. The results showed that the Thompson model had the best fitness to experimental data for drying of both fresh and infused blueberries. The predicted data using the Thompson model are shown in Fig. 3. The Thompson model is an empirical model proposed to fit the experimental data of convectional air-drying of corn (Thompson, Peart, & Foster, 1968), but it was widely used for drying of vegetables and fruits (Kashaninejad, Mortazavi, Safekordi, & Tabil, 2007; Menges & Ertekin, 2006). The good fitness of the Thompson model to drying corn and blueberries might be because both have a waxy layer on their surfaces. Most dried fruits and vegetables do not have a waxy layer or have their surface skin removed or are cut into slices before drying. Compared with fresh blueberries, the effect of such a waxy layer on the drying process could be less for sugar-infused blueberries because the structure of the waxy layer might be changed during the freezing process before sugar infusion (Fava, Alzamora, & Castro, 2006).

Page's model and modified Page's model showed the best fitness to the experimental data of sugar-infused blueberries, but not for fresh blueberries. The difference is likely due to the cracks and structure change of frozen blueberries used for infusion. Therefore, the resistance of waxy layer to drying was reduced. This is similar to sliced or cut materials reported in previous researches, in which the Page model and modified model have been successfully applied (Bozkir, 2006; Doymaz, 2005; Doymaz, 2006; Jain & Pathare, 2004; Kaleemullah & Kailappan, 2006).

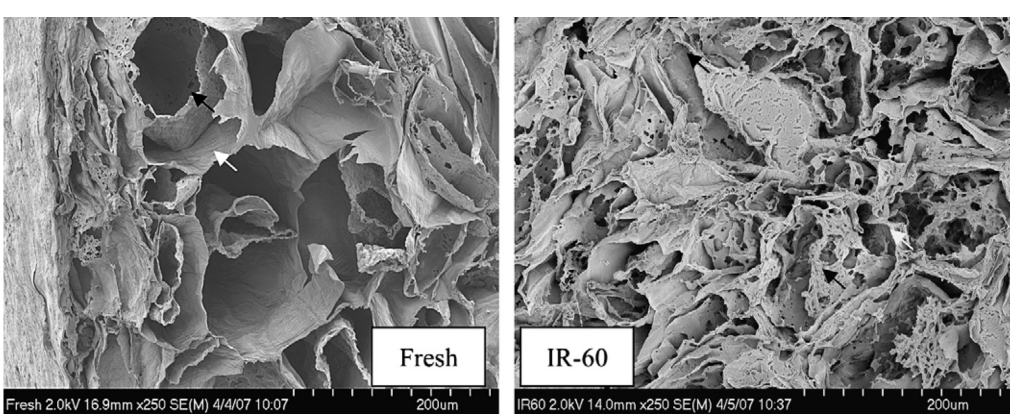

Fig. 8. Changes in plasma membrane (black arrow) and cell wall (white arrow) of tissue cells in fresh blueberries before drying (left) and after drying for 60 min with IR at 70 °C (right).

Table 3
Fitness of different models for IR drying of blueberries

Codes of models	Models	Fresh blueberries			Infused blueberries		
		R^2	χ^2	RMSE	R^2	χ^2	RMSE
6	$t = a[\ln(\mathrm{MR})]^2 + b[\ln(\mathrm{MR})]$	0.9956^{a}	0.00078^{b}	0.00675^{b}	0.9986^{a}	0.00011^{d}	0.00235^{e}
7	$\mathrm{MR} = \exp[-(at^2 + bt)]$	0.9939^{a}	0.00143^{b}	0.00929^{b}	0.9926^{a}	0.00065^{cd}	0.00672^{cd}
8	$t = a\mathrm{MR}^2 + b\mathrm{MR} + c$	0.9893^{a}	0.00149^{b}	0.00748^{b}	0.9941^{a}	0.00028^{cd}	0.00434^{de}
2	$\mathrm{MR} = at^2 + bt + 1$	0.9889^{a}	0.00967^{a}	0.03806^{a}	0.9700^{b}	0.00171^{b}	0.01089^{b}
4	$\mathrm{MR} = \exp[-kt^n)$	0.9874^{a}	0.00203^{b}	0.00787^{b}	0.9971^{a}	0.00008^{d}	0.00211^{e}
5	$\mathrm{MR} = \exp[-(kt)^n]$	0.9870^{a}	0.00105^{b}	0.00791^{b}	0.9972^{a}	0.00008^{d}	0.00213^{e}
1	$\mathrm{MR} = a\ \exp(-kt)$	0.9750^{b}	0.0025^{b}	0.01056^{b}	0.9768^{b}	0.00081^{c}	0.00735^{c}
3	$\mathrm{MR} = \exp(-kt)$	0.9718^{b}	0.00431^{ab}	0.01516^{a}	0.9490^{c}	0.0035^{a}	0.01564^{a}

Note: Mean values followed by different letters in a same column are significant different at $p < 0.05$.

The regression models, $\mathrm{MR} = \exp[-(at^2 + bt)]$ and $t = a\mathrm{MR}^2 + b\mathrm{MR} + c$ also showed good agreement with the experimental data for fresh blueberries and sugar-infused blueberries (average of $R^2 > 0.989$, $p < 0.05$). For fresh blueberry drying, they fit the experimental data better than all other models except the Thompson model. For infused blueberry drying, the fitness of the two models was slightly lower than Thompson, Page and modified Page models. Therefore, these two models could also be used for prediction of IR drying process of fresh blueberries and sugar-infused blueberries. The constants of the five best models are listed in Table 4.

3.3. Color and texture of dried blueberries

In general, the IR dried blueberries were much firmer in texture and darker, redder and less blue in color than the undried blueberries and the blueberries dried with hot air. The IR dried product also had a greater color change than hot air dried berries. Compared with the IR dried noninfused products, the IR dried infused products were much firmer, more cohesive, chewier and less springy in texture due to their higher solid contents, similar to what happened in air-drying of sugar-infused blueberries (Nsonzi & Ramaswamy, 1998) and other fruits (Fernandes, Rodrigues, Gaspareto, & Oliveira, 2006). Although they had lower L and a color quality values and higher b value compared with fresh blueberries, the color of both dried fresh and infused products were very similar by visual observation.

The effect of drying temperature on texture and color quality did not show any significant trend for either fresh or sugar-infused blueberries. The texture and color of products dried with different temperatures varied in relatively narrow ranges. Compared with other IR drying temperatures, 70 and 80 °C gave dried products with higher springiness, cohesiveness, chewiness and the lower total change of color for fresh blueberries and sugar-infused blueberries, respectively. In the tests, we observed that many fresh blueberries were cracked during IR drying, resulting in a strong burning smell when the drying temperature was above 80 °C. Such problem was not found for sugar-infused blueberries due to the much shorter drying time and lower moisture content in the berries. Therefore, 70 and 80 °C are recommended for IR drying of fresh blueberries and sugar-infused blueberries, respectively, to achieve a good balance of time economy and high quality product. In previous research, 70 °C drying temperature was also found to be the optimal temperature for fresh and individually quick frozen blueberries under convectional air-drying because it gave high moisture efficiency and drying rate (Eidt & Macarthur, 1944; MacGregor, 2005).

4. Conclusions

IR drying produced much firmer-texture product with much increased drying efficiency for fresh blueberries and sugar-infused blueberries compared to convectional air-drying. Increasing the temperature from 60 to 80 °C, showed great

Table 4
Model constants for IR drying of blueberries

		Models										
		$t = a[\ln(\mathrm{MR})\ ]^2 + b[\ln(\mathrm{MR})]$		$\mathrm{MR} = \exp\ [-(at^2 + bt)]$		$t = a\mathrm{MR}^2 + b\mathrm{MR} + c$			$\mathrm{MR} = \exp\ [-(kt)^n]$		$\mathrm{MR} = \exp\ (-kt^n)$	
		a	b	a	b	a	b	c	k	n	k	n
Fresh blueberries	Hot air-60 °C	−20.232	−371.09	0.0000006	0.0026	1154.7	−2082.3	967.58				
	IR-60 °C	−36.561	−238.12	0.000006	0.0025	377.79	−725.71	547.02				
	IR-70 °C	−11.859	−102.53	0.00004	0.0078	177.9	−383.49	211.78				
	IR-80 °C	−6.2698	−57.198	0.0001	0.0141	111.38	−230.14	122.38				
	IR-90 °C	−3.3265	−37.622	0.0001	0.0239	90.286	−172.76	87.207				
Sugar-infused blueberries	IR-60 °C	159.86	−122.02	−0.000007	0.0056	727.15	−1419.6	700.56	0.0034	0.6801	0.0211	0.6801
	IR-70 °C	58.602	−37.422	−0.00006	0.0163	299.34	−555.63	260.47	0.0106	0.6908	0.0432	0.6908
	IR-80 °C	25.02	−25.75	−0.0002	0.0287	140.46	−271.21	131.56	0.0196	0.6925	0.0656	0.6926
	IR-90 °C	24.73	−20.016	−0.0003	0.0342	125.13	−239.42	115.37	0.0229	0.7211	0.0656	0.7211

enhancement of drying rate and reduction of drying time without causing significant negative influence on the quality of dried products. The effective moisture diffusivity and activation energy were higher for fresh blueberries than that for sugar-infused blueberries under IR drying. Thompson model showed best fitness to IR drying of both fresh and sugar-infused blueberries.

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