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Research Article

DRYING OF BLACK CARROT POMACE IN AN INFRARED DRYER: KINETICS, MODELLING AND ENERGY EFFICIENCY

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ABSTRACT

The effect of different infrared power levels on drying kinetics of black carrot pomace was investigated in this study. The black carrot pomace dried at 104, 146, 188 and 230 W infrared powers. An increase in the infrared power resulted in a significant reduction in the drying time. Five mathematical models were used to represent experimental data. The Midilli et al. model is satisfactorily described drying kinetics. The values of effective diffusivity were calculated in a range of 0.58 to 2.94×10^{-9} m^2/s and increased with the infrared power increase. The activation energy was estimated by a modified Arrhenius type equation and calculated to be 3.65 kW/kg. The highest energy efficiency was recorded for the samples dried at 230 W.

Keywords: Activation energy, black carrot pomace, effective diffusivity, energy efficiency, infrared drying, mathematical modeling.

1. INTRODUCTION

Black or purple carrot (*Daucus carota* L. ssp. *sativus* var. *atrorubens* Alef.) originated from Turkey, Middle East, and the Far East, where it has been cultivated for at least 3000 years [1]. They are commonly used in juices, candies, confectionery, ice cream, soft drinks, or other fermented beverages [2].

By-products, wastes, and pomaces of food juice processing, which represent a major disposal problem for the industry concerned, are very promising sources of value-added substances [3]. Black carrot pomace is considered to be treated as production waste and the contained valuable products, such as dietary fiber and soluble components of cell sap. Moreover, it may be used in powdered form as a coloring additive as well as a source of dietary fiber and as an antioxidant component of different dry and liquid products [4].

Carrot juice (orange and black) sector generates large quantities of carrot pomace. The processed black carrot pomace generally has high moisture contents, and need to the removal of moisture before the production of high-added value products. Drying has always been of great importance to the preservation of agricultural by-products and pomaces.

Infrared (IR) drying has gained popularity as an alternative drying method for a variety of agricultural products. When infrared radiation is used to heat or dry moist materials, penetrates it and the energy of radiation converts into heat. When a material is exposed to infrared radiation,

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both the surface and the inner layers are heated intensely, resulting in a high rate of heat and mass transfer compared with conventional drying [5]. The use of infrared radiation technology in drying agricultural products has several advantages. These may include decreased drying time, high energy efficiency, high-quality finished products, and uniform temperature in the product [6,7]. Several agricultural products and by-products have been successfully dried by the infrared application and by a combined infrared-assisted convection process such as onion [7], apple pomace [8], red pepper [9], and tomato by-products [10]. However, the drying process of black or purple pomace has not been investigated to a great extent, and a few data are available in the literature. Janiszewska et al. [11] studied that the effect of four drying methods (convective, infrared-convective, microwave-convective and freeze drying) on the physical properties of purple carrot pomace. The main objectives of this study were to investigate the effect of infrared power levels on the drying rate and time, fit the experimental data to five thin-layer drying models, and compute effective diffusivity, activation energy and energy efficiency of black carrot pomace.

2. MATERIAL AND METHODS

2.1. Material

Black carrot pomace, which is a waste material of carrot juice processing, was provided by Döhler Natural Food & Beverage Ingredients Factory, Karaman, Turkey. The initial moisture content of black carrot pomace was determined by using the oven method at 110°C for 24 h. Triplicate samples were used for the determination of moisture content, and the average values were reported as 81.4%, w.b. (4.376 kg water/kg dry matter, d.b.).

2.2. Drying Procedure

In this study, drying experiments were carried out in a moisture analyzer with one 250 W halogen lamp (Snijders Moisture Balance, Snijders b.v., Tilburg, Holland). The infrared drying process, the sample should be separated evenly and homogeneously over the entire pan. The experiments were performed at infrared power levels varying from 104 to 230 W. The power level was set in the control unit of equipment. Moisture loss in the samples with an initial load of 60±0.2 g and thickness of about 11 mm was measured with a digital balance (Mettler-Toledo AG, Grefensee, Switzerland, model BB3000) with an accuracy of 0.1 g and recorded at 10 min intervals. The drying process was continued until the moisture content of the sample was remained at about 1.5%±0.2 (w.b.). The dried product was cooled and packed in low-density polyethylene bags that were heat-sealed. All experiments were conducted in duplicate, and the average of the moisture content at each value was used for drawing the drying curves.

2.3. Mathematical Modelling

The data derived from the drying of black carrot pomace was fitted with five drying models (Table 1) typically used for the modeling of drying curves. The moisture ratio (*MR*) of the samples is defined according to Eq. (1):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

where M_t, M_0 and M_e are moisture content at any time, initial moisture content, and equilibrium moisture content (kg water/kg dry matter), respectively, t is drying time (min). The moisture ratio *(MR)* was simplified to M_t/M_0 instead of $(M_t - M_e)/(M_0 - M_e)$ by some investigators [15,16] because of the values of M_e small compared with M_t or M_0 for long drying time.

Table 1. Mathematical models applied to the drying curves

Model name	***Model***	***Reference***
Lewis	$MR = \exp(-kt)$	[11]
Henderson and Pabis	$MR = a\exp(-kt)$	[12]
Logarithmic	$MR = a\exp(-kt) + c$	[13]
Page	$MR = \exp(-kt^n)$	[8]
Midilli et al.	$MR = a\exp(-kt^n) + bt$	[14]

*a, b, c, k, n: E*mpirical constants and coefficient in the drying models

The IR drying rates *(DR)* of black carrot pomace was calculated using Eq. (2):

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \tag{2}$$

where $M_{t+\Delta t}$ is moisture content at $t+\Delta t$ (kg water/kg dry matter), and t is time (min).

2.4. Statistical Analysis

Data were analyzed using Statistica 8.0.550 (StatSoft Inc., Tulsa, OK, USA) software package. The parameters of models were estimated using a non-linear regression procedure based on the Levenberg-Marquardt algorithm. The fitting quality of the experimental data to all models was evaluated using the coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (*RMSE*). These parameters were calculated from the following formulas:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \tag{3}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2\right]^{1/2} \tag{4}$$

where $MR_{exp,i}$ and $MR_{pre,i}$ are experimental and predicted dimensionless moisture ratios, respectively; *N* is number of observations; *z* is number of constants. The best model describing the drying characteristics of samples was chosen as the one with the highest R^2, the least χ^2 and *RMSE* [10,17].

2.5. Determination of Effective Diffusivity and Activation Energy

Drying of most food materials occurs in the falling-rate period and moisture transfer during the drying process is controlled by internal diffusion. Fick's second diffusion equation has been widely used to describe the drying process for agricultural materials. The diffusion equation is solved for an infinite slab, assuming unidimensional moisture movement volume change, constant temperature, and diffusivity coefficients, and negligible shrinkage and external resistance [18]:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right) \tag{5}$$

where D_{eff} is the effective moisture diffusivity (m^2/s); *L* is the half thickness of the slab (m), and *n* is the positive integer. For long drying times Eq. (5) simplifies to a limiting form of the diffusion equation as follows:

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4L^2}\right) \tag{6}$$

The slope *(K)* is calculated by plotting *ln (MR)* versus *time* according to Eq. (6).

$$K = \frac{\pi^2 D_{eff}}{4L^2} \tag{7}$$

Temperature is not a directly measurable quantity in the infrared power level during the drying process in this study. For the calculation of activation energy, a modified form of the Arrhenius equation as derived by Dadali and Ozbek [19] shows the relationship between the effective diffusivity and the infrared power level to sample weight.

$$D_{eff} = D_0\, exp\left(-\frac{E_a\, m}{p}\right) \tag{8}$$

where D_0 is the pre-exponential factor of Arrhenius equation (m^2/s), E_a is the activation energy (W/kg), *P* is the infrared power level (W), and m is the sample weight (kg).

2.6. Drying Efficiency

The infrared drying efficiency was calculated as the ratio of heat energy utilized for evaporating water from black carrot pomace to the heat supplied by the dryer [20].

$$\eta = \frac{m_w\,\lambda_w}{p\,t}\times 100 \tag{9}$$

where η is the infrared drying efficiency (%), p is the infrared power (W), m_w is the weight of evaporated water (g), and λ_w is the latent heat for vaporization of water (2257 J/g).

3. RESULTS AND DISCUSSION

3.1. Drying Characteristics

The effects of infrared power on moisture content with drying time are shown in Figure 1. According to the results in Figure 1, the infrared power level had a significant effect on the moisture content of the black carrot pomace as expected. The results showed that drying time decreased greatly when the infrared power level increased. The drying time required to reach the final moisture content of samples were 320, 180, 100 and 60 min at the infrared power levels of 104, 146, 188 and 230 W, respectively. The average drying rates increased 5.33 times as infrared power level increased from 104 W to 230 W. The decrease in drying time with an increase in the infrared power level has been reported by Sharma et al. [7] for onion slices, Nasiroglu and Kocabiyik [9] for red pepper slices, and Kocabiyik and Tezer [21] for carrot slices.

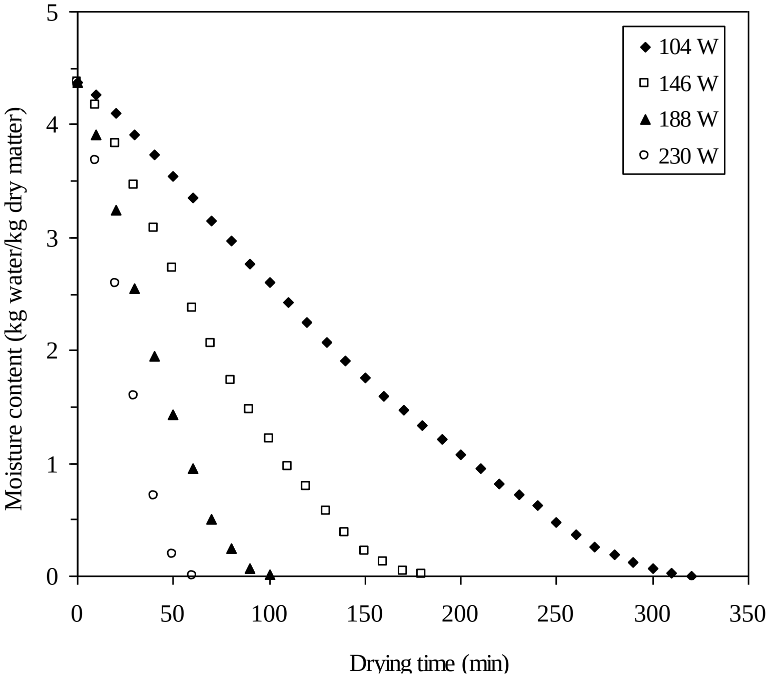


Figure 1. Drying curves of black carrot pomace at different power levels

The drying rate curves of black carrot pomace are shown in Figure 2. It is clear that the drying rate decrease continuously with moisture content. During drying, the drying rates were higher in the beginning of the process, and after that decreased with the decrease of moisture content in the samples. The reason for the reduction of drying rate might be due to a reduction in porosity of samples due to shrinkage with advancement, which increased the resistance to movement of water leading to further fall in drying rates [22]. This observation is in agreement with previous studies on infrared drying of food by-products [3,8,10].

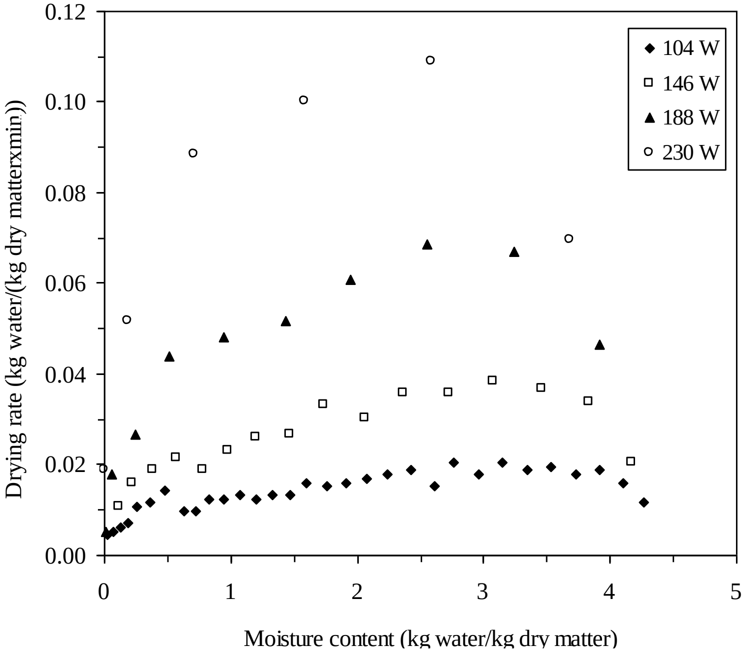


Figure 2. Drying rate curves of black carrot pomace determined at different power levels

3.2. Fitting of the Drying Curves

The moisture content data obtained from the drying experiments were fitted with five thin-layer drying models identified in Table 1. The best model selected based on the highest R^2 and the lowest χ^2 and *RMSE* values. Results of the statistical computing are shown in Table 2. The R^2 values for all models were above 0.92, and that for Lewis and Henderson and Pabis models were lower. The statistical parameter estimations showed that R^2, χ^2 and *RMSE* values were ranged from 0.9291 to 0.9997, 0.000038 to 0.010993, and 0.017184 to 0.37708, respectively. Among the five models, the Midilli et al. model fitted the best with experimental drying data for black carrot pomace, with the highest R^2 for all power levels. The $\chi^2$and *RMSE* also showed the best results with the smaller values. It is clear that, the R^2, χ^2 and *RMSE* values of this model were changed between 0.9993-0.9997, 0.000038-0.000178 and 0.017184-0.048890, respectively. Figure 3 compares experimental data with those predicted with the Midilli et al. model for black carrot pomace. The prediction using those models showed MR values banded along the straight line and showed the suitability in describing drying kinetics of black carrot pomace.

Table 2. Statistical analysis of models at different infrared power levels

Model	*p (W)*	*Model constants and coefficients*	R^2	χ^2	*RMSE*
Lewis	104	k: 0.00667	0.9441	0.005771	0.377083
	146	k: 0.01261	0.9462	0.006132	0.293176
	188	k: 0.02347	0.9450	0.007151	0.235803
	230	k: 0.03649	0.9291	0.010993	0.221662
Henderson and Pabis	104	a: 1.12217, k: 0.00750	0.9623	0.004014	0.302687
	146	a: 1.11914, k: 0.01408	0.9632	0.004438	0.239673
	188	a: 1.09954, k: 0.02565	0.9576	0.006129	0.217493
	230	a: 1.08720, k: 0.03934	0.9398	0.011176	0.225417
Logarithmic	104	a: 1.88900, k: 0.00313, c: -0.65067	0.9981	0.000198	0.059350
	146	a: 1.54097, k: 0.00677, c: -0.49227	0.9962	0.000481	0.072748
	188	a: 1.52147, k: 0.01255, c: -0.47841	0.9930	0.001129	0.080572
	230	a: 1.82128, k: 0.01512, c: -0.78193	0.9876	0.002871	0.099992
Page	104	k: 0.00046, n: 1.52607	0.9940	0.000630	0.120517
	146	k: 0.00106, n: 1.55358	0.9966	0.000406	0.070732
	188	k: 0.00222, n: 1.60945	0.9869	0.000444	0.056228
	230	k: 0.00229, n: 1.81052	0.9977	0.000411	0.035257
Midilli et al.	104	a: 0.99827, b: -0.00045, k: 0.00111, n: 1.30137	0.9996	0.000041	0.017184
	146	a: 1.00023, b: -0.00049, k: 0.00190, n: 1.38720	0.9997	0.000038	0.048890
	188	a: 0.99586, b: -0.00065, k: 0.00321, n: 1.48138	0.9993	0.000126	0.026047
	230	a: 0.99601, b: -0.00085, k: 0.00300, n: 1.70041	0.9994	0.000178	0.020592

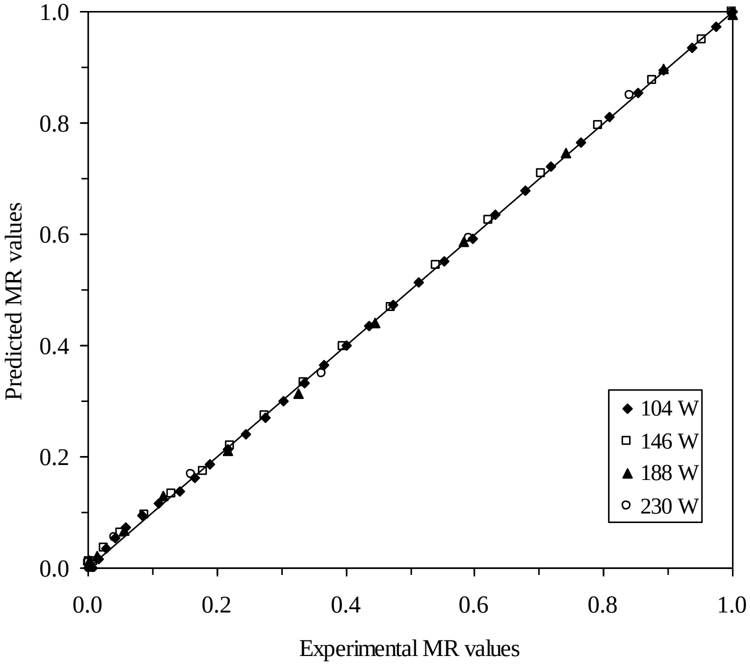


Figure 3. Experimental vs. predicted moisture ratios using Midilli et al. model for different power levels

3.3. Effective Diffusivity

The values of effective diffusivity (D_{eff}) were calculated using Eq. (7) and are shown in Figure 4. The D_{eff} values of black carrot pomace in the infrared drying process at 104-230 W varied in the range of $0.58\text{-}2.94\times10^{-9}$ m^2/s. It can be seen that D_{eff} values increased greatly with increasing infrared power level. Drying at 230 W has the highest value of D_{eff}, and the lowest value was obtained for 104 W. The values of D_{eff} from this study lie within in general range 10^{-12} to 10^{-8} m^2/s for drying of food materials [23]. This result is similar to the results for hot-air drying of carrot pomace [24], hot-air drying of apple pomace [8], and infrared drying of tomato by-products [10]. The effect of infrared power on effective diffusivity is defined by the following equation:

$$D_{eff} = 4\times10^{-11}p - 2\times10^{-9} \qquad (R^2 = 0.9955) \qquad (10)$$

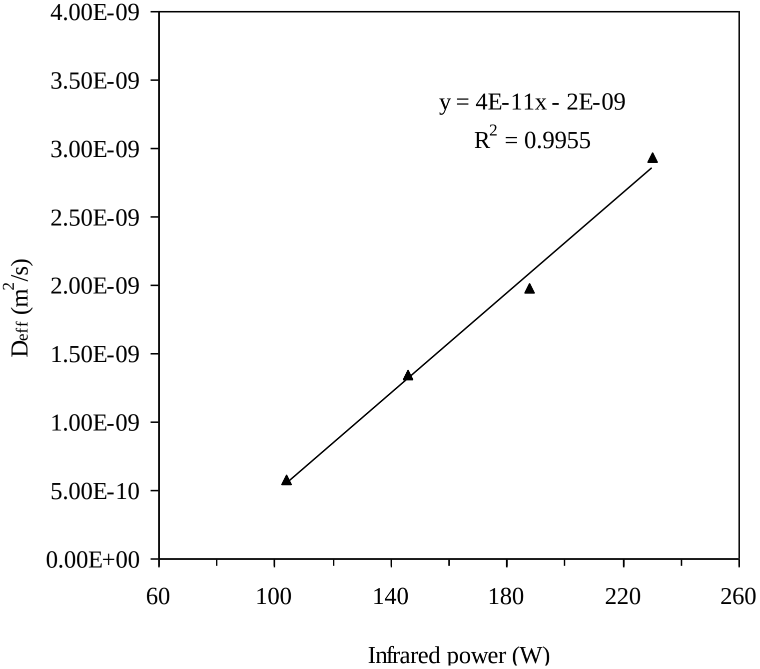


Figure 4. Variation of effective moisture diffusivity with power levels

3.4. Activation Energy

The activation energy can be determined from the slope of Arrhenius plot, *ln* (D_{eff}) versus *m/p* (Eq. 8). The *ln* (D_{eff}) as a function of the sample weight/infrared power level was plotted in Figure 5. The slope of the line is $(-E_a)$, and the intercept equals to ln (D_0). The results show a linear relationship due to Arrhenius type dependence. Eq. (11) shows the effect of sample weight/power level on D_{eff} of samples with the following coefficients:

$$D_{eff} = 4.5188 \times 10^{-9} exp\left(-\frac{3651\ m}{p}\right) \qquad (R^2 = 0.9345) \quad (11)$$

The estimated values of D_0 and E_a from modified Arrhenius type exponential Eg. (11) are 4.5188×10^{-9} m^2/s and 3.65 kW/kg, respectively.

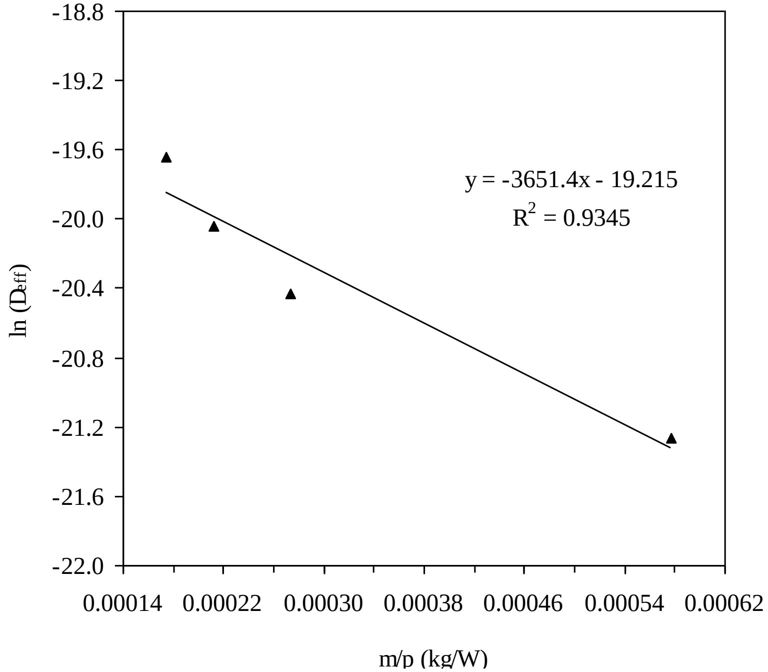


Figure 5. Arrhenius-type relationship between effective diffusivity and power levels

3.5. Energy Efficiency

The values of energy efficiency calculated using Eq. (9). The variation of energy efficiency with drying time for infrared drying of black carrot pomace shows in Figure 6. The energy efficiency was very high during the initial period of the drying which resulted in a higher absorption of infrared power. Following moisture in the samples, the energy absorbed by the samples decreased and reflected power increased. The best result about energy efficiency was obtained from 230 W infrared power levels. Average energy efficiency of black carrot pomace ranged from 4.70% to 12.75% for the output power level.

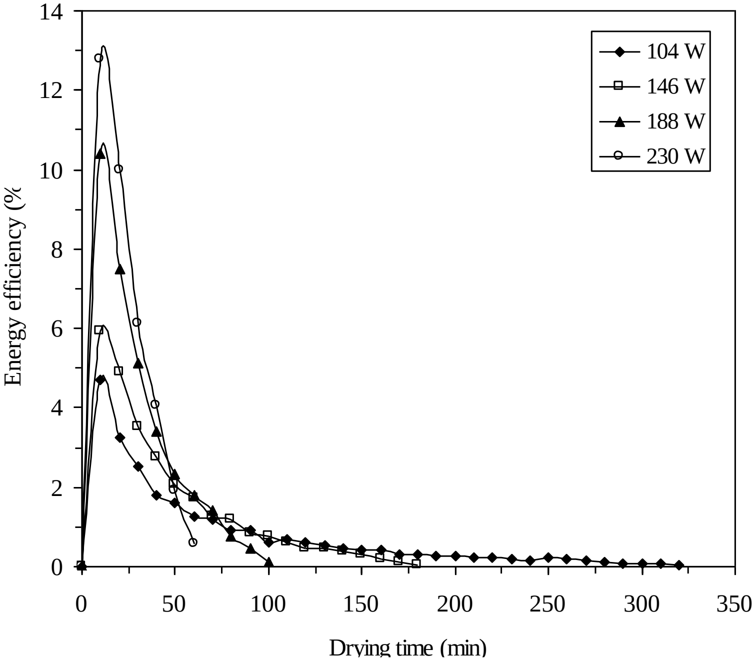
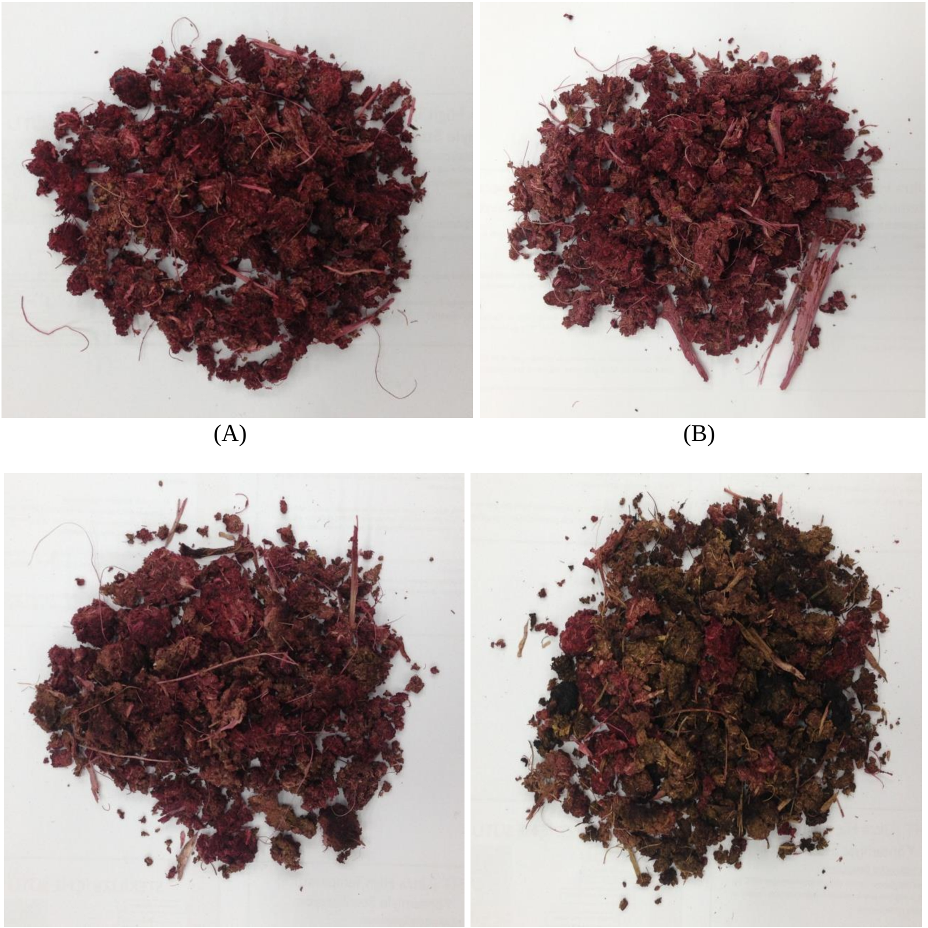


Figure 6. Energy efficiency versus drying time for infrared drying of black carrot pomace

3.6. Colour and Appearance

Colour is a major attribute of dried food products. To facilitate the comparison of colour and appearance of the samples, a digital picture was taken from each dried sample. Figure 7 shows the pictures of the dried black carrot pomace samples at different infrared power levels. It was found that with an increase of the power level, the colour became darker implying that more browning of the black carrot pomace occurred. As a result, the colour and appearance of the dried samples at 104 W gave superior quality dried black carrot pomace.



(D)

Figure 7. Photographs of dried black carrot pomace after drying at different power levels (A: 104 W, B: 146 W, C: 188 W, and D: 230 W).

4. CONCLUSIONS

Based on the results of this study, the following conclusions were drawn:

a) As the infrared power level increases, drying rate increases and drying time decreases.

b) The Midilli et al. model gave the best representations of drying data under all experimental conditions.

c) The effective diffusivity varied between 0.58 and 2.94×10^{-9} m^2/s and increases as infrared power increases.

d) The activation energy was estimated by a modified Arrhenius type equation and found to be 3.65 kW/kg.

e) The highest energy efficiency was recorded for the samples dried at 230 W.

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