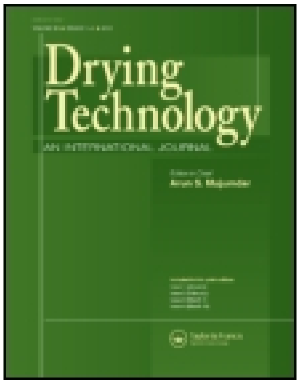

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Combined Infrared-Convective Drying of Murta (Ugni molinae Turcz) Berries: Kinetic Modeling and Quality Assessment

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Combined Infrared-Convective Drying of Murta (*Ugni molinae* Turcz) Berries: Kinetic Modeling and Quality Assessment

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Murta (*Ugni molinae* Turcz) berries were dried under convective and combined convective-infrared conditions at 40, 50 and 60°C and 400–800 W in order to determine the drying characteristics and to compare the dried product's quality. To model the drying kinetics, seven mathematical equations were fitted to experimental data. According to statistical tests performed, the Midilli-Kuçuk model best fitted experimental data and was closely followed by the logarithmic model. Effective moisture diffusivity also showed dependency on drying conditions and varied between 7.59×10^{-10} to 44.18×10^{-10} m^2/s and 11.34×10^{-10} to 85.41×10^{-10} m^2/s for air-convective drying and combined infrared-convective drying. As to quality attributes of the berries, total surface color difference (ΔE) and total phenolic content (TPC) were determined. It was found that chromaticity coefficients a* and b* changed significantly, showing ΔE to be dependent on the mode of heat supply. TPC under all drying conditions decreased and was significantly different from the initial value in fresh samples. However, at a constant drying temperature, an increase in infrared power enhanced retention of TPC in samples. In particular, working at 40°C/800 W resulted in dried samples with the highest TPC.

Keywords Drying kinetics modeling; Infrared drying; Murta berries; Quality of dried fruit

INTRODUCTION

Dehydration is a postharvest technology that prolongs the shelf-life of foods, preserving their quality and stability by lowering water activity, thus avoiding spoilage and contamination during storage.[1] In order to fulfill efficiently the drying process, shortening operation times and enhancing final products quality, combined drying methods in which different sources of energy are involved are becoming more and more widespread.[2–4] This is the case of convective-infrared drying of foods. When foods are subjected to a microwave field, the wave penetrates directly into the material, resulting in fast volumetric heating (from inside to outside). A quick energy absorption by water molecules causes rapid evaporation of water, creating an outward flux of rapidly escaping water vapor. In addition to improving drying rate, this outward flux helps to prevent the shrinkage of the tissue structure.[5] Furthermore, heat and mass transfer are more efficient than during convective drying, leading consequently to a drastic reduction in drying time, increasing energy efficiency and decreasing specific energy consumption. Several studies have reported on the benefits brought to quality of infrared-heated products.[5,6] Infrared drying can therefore be seen as a convenient alternative method to convective drying of heat-sensitive products like fruits.

Murta (*Ugni molinae* Turcz), also known as murtilla or Chilean guava, is an edible berry from a forest understorey shrub growing wildly in the southern regions of Chile.[7] Murta, like other berries from South America, possesses a rich and diversified composition of bioactive compounds with health-promoting properties.[8–10] In particular, its relatively high content of polyphenol compounds could be seen as a new source of antioxidants.[11,12] Apart from being consumed as a fresh fruit during the summer, dried berries are often used as food ingredients as well as in preparation of fruit infusion or tea.[13] Due to its pleasant fruit aroma, murta has a great potential for commercialization in a dried state.[14]

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In order to successfully transfer knowledge acquired experimentally from studies on food dehydration into industrial applications, mathematical modeling of drying kinetics is required. Moreover, a mathematical model is an important tool used to optimize management of operating parameters and to predict performance of a drying system.[15] Numerous mathematical models, empirical and semi-empirical, have been proposed to estimate the drying characteristics of agricultural products. These simple models, also known as thin layer models, allow prediction of mass transfer during dehydration and are applied to simulate drying curves under similar conditions.[13,16,17]

Economic and technical advantages of different methods of dehydration must be accompanied by a high quality of the final product, which should fulfill consumers' expectation. For food industry applications, the color of murta and their phenols content are among the most important quality attributes. To our knowledge, no work is available on the effect of infrared drying on color and total phenolic content of murta berries. Therefore, the aim of this study was to obtain mathematical models for the drying kinetics of murta berries subjected to convective and combined convective-infrared drying at 40, 50, and 60°C and 400–800 W. Diffusional and empirical models were applied to estimate and compare variation of moisture content during the dehydration process of murta under different conditions. Moreover, the effect of processing on quality attributes, like surface color and total phenolic content, as well as on energy consumption was also evaluated.

MATERIALS AND METHODS

Raw Material and Drying Process

Murta (*Ugni molinae* Turcz) berries were purchased in the city of Valdivia, Chile. Samples were selected to provide a homogeneous group, based on their color, size, and freshness according to visual analysis. They were stored at 4.5 ± 0.2°C and 92.3 ± 0.4% relative humidity in a refrigerator (Samsung SR-34RMB, Seoul, South Korea). The moisture content was determined according to AOAC methodology No. 934.06 using an analytical balance (Mettler Toledo XS205 DU, Schwerzenbach, Switzerland) with an accuracy of $\pm$ 0.01 mg.[18] All the analyses were performed in triplicate and expressed in g/100 g fresh product.

Drying experiments were performed in triplicate and carried out at air temperatures of 40, 50, and 60°C in a laboratory dryer, maintaining a constant air flow of 1.5 ± 0.2 m/s. Figure 1 shows a scheme of the dryer used in this study. The samples of murta berries were arranged as a thin layer in a stainless-steel basket with a load density of 8.0 ± 0.2 kg/m^2. Infrared radiation (400 and 800 W) was also applied combined with air convection. Weight of samples was monitored using an analytical balance (Ohaus, SP402, NJ, USA) and data was registered by a system interface (Ohaus, RS232, USA) connected to a PC. The experiments ended at the point of reaching constant weight or equilibrium conditions.

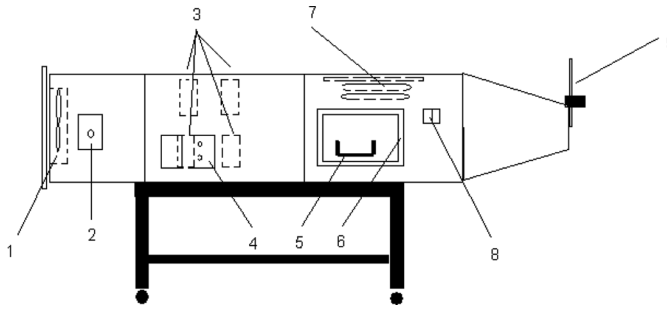

FIG. 1. Schematic view of infrared-convective dryer.

Determination of Effective Moisture Diffusivity

Fick's second law of diffusion (Eq. (1)) was used to model the drying kinetics, since moisture diffusion is one of the main mass transport mechanisms that describe the drying process.[16] In this model, the dependent variable is moisture ratio (MR), which relates the gradient of sample moisture content in real time to both initial and equilibrium moisture contents, Eq. (2). Sample equilibrium moisture content (X_{we}) was determined by means of the GAB equation developed in previous work.[13]

$$\frac{\partial MR}{\partial t} = D_{eff}\left[\frac{\partial^2 MR}{\partial r^2} + \frac{2}{r}\frac{\partial MR}{\partial r}\right] \tag{1}$$

$$MR = \frac{X_{wt} - X_{we}}{X_{wo} - X_{we}} \tag{2}$$

For simplicity, it was assumed that (1) murta berry has a spherical shape with radius, r; (2) effective moisture diffusivity is homogeneous throughout the fruit; (3) moisture moves radially from inside of the fruit and through its surface; (4) shrinkage during drying is negligible; and (5) mass transfer is symmetric. Moisture distribution was also considered initially uniform in the whole fruit. Under these assumptions, the solution of Eq. (1) is obtained and shown in Eq. (3).[19]

$$MR = \frac{6}{\pi^2}\exp\left[\frac{D_{eff}\,\pi^2\,t}{r^2}\right] \tag{3}$$

Equation (3) is applied to estimate the effective moisture diffusivity. A linear relationship between natural logarithm of MR and time is obtained, which can be used to determine effective moisture diffusivity (D_{eff}).

The effective moisture diffusivity can be related to temperature by an Arrhenius-type relationship, as given in Eq. (4). Activation energy was calculated by plotting the natural logarithm of D_{eff} against the reciprocal of absolute temperature.

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{4}$$

Mathematical Modeling of Drying Kinetics

Different mathematical models have been proposed to describe the drying kinetics of food and bio-products and are derived from the diffusional model of Fick's second law for different geometries and contour conditions.[20–22] Table 1 shows the mathematical expressions of the selected models that were used to fit the experimental drying data of murta berries.[13]

Energy Consumption

The amount of energy consumed by the dryer for the different drying treatments was estimated according to previous investigations.[23]

Quality Parameters

Surface Color

Color of murta samples was measured by a colorimeter (HunterLab, MiniScan™ XE Plus, Reston, VA, USA) and described by CIE coordinates, L^* (whiteness or brightness), a^* (redness/greenness), and b^* (yellowness/blueness) at standard illuminant D_{65} and observer angle of 10°.[1] Five replicate measurements were performed and results were averaged. The total color difference ($\triangle E$) was calculated using Eq. (5), where L_o, a_o, and b_o are the control values for fresh murta fruit.

$$\Delta E = \left[(a^* - a_0)^2 + (b^* - b_0)^2 + (L^* - L_0)^2\right]^{0.5} \tag{5}$$

TABLE 1
Mathematical models selected to describe the drying kinetics of murta berry

Model name	Model equation
Page	$MR = \exp(-k_1\ t^{n_1})$
Modified Page	$MR = \exp(-(k_2\ t)^{n_2})$
Logarithmic	$MR = n_3 + n_4 \cdot \exp(-k_3 t)$
Two-term	$MR = n_5 \exp(-k_4 t) + n_6 \exp(-k_5 t)$
Modified Henderson-Pabis	$MR = n_7 \exp(-k_6 t) + n_8 \exp(-k_7 t) + n_9 \exp(-k_8 t)$
Midilli-Kuçuk	$MR = n_{10} \exp(-k_9\ t^{n_{11}}) + n_{12}\ t$
Weibull	$MR = \exp\left(-\left(\frac{t}{\beta}\right)^{\alpha}\right)$

Total Phenolic Content

Total phenolic content (TPC) was determined colorimetrically using the Folin-Ciocalteu reagent (FC).[24] 0.5 mL aliquot of the murta extract was transferred to a glass tube; 0.5 mL of FC reagent was added after 5 min followed by 2 mL of Na_2CO_3 solution (200 mg/ mL). The sample was mixed on a vortex mixer and the reaction proceeded for 15 min at ambient temperature. Afterwards, 10 mL of ultra-pure water were added and the precipitate formed was removed by centrifugation for 5 min at 4000 g. Finally, absorbance was measured at 725 nm using a spectrophotometer (Spectronic® 20 GenesysTM131, Illinois, USA) and compared to a gallic acid (GA) calibration curve. Results were expressed as mg GA/100 g dry matter. All reagents were purchased from Merck (Merck KGaA, Darmstadt, Germany) and all measurements were done in triplicate.

Statistical Analysis

For modeling the drying kinetics, the goodness of fit between predicted and experimental data was evaluated based on statistical analyses, which included sum squared error (Eq. (6)), root mean squared error (Eq. (7)), and chi-square (Eq. (8)).[16,17] The effect of convective and infrared drying on water diffusion coefficients and empirical parameters was estimated using Statgraphics Plus® 5.1 (Statistical Graphics Corp., Herndon, VA, USA). The results were analyzed by an analysis of variance (ANOVA). Differences between the media were analyzed using the least significant difference (LSD) test with a significance level of $\alpha = 0.05$ and a confidence interval of 95% (p-value <0.05). In addition, the multiple range test (MRT) was used to demonstrate the existence of homogeneous groups.

$$SSE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{calc,i}\right)^2 \tag{6}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{calc,i} - MR_{\exp,i}\right)^2\right]^{1/2} \tag{7}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{calc,i}\right)^2}{N - m} \tag{8}$$

RESULTS AND DISCUSSION

Drying Kinetics

The initial moisture content of the murta samples was 4.21 ± 0.20 kg water/kg dry matter. As expected, hot air temperature and infrared power affected the drying characteristics of murta berries. These factors appear to have positive effects on mass transfer, which translated into shorter drying time. Figure 2 shows the profile of moisture ratio (MR) during dehydration of murta berries under different conditions in terms of temperature and infrared power. Results showed that an increase in drying temperature led to a decrease in the time required to achieve definite moisture content. For example, at a constant drying temperature of 60°C, the process time required to reach final moisture content of $MR = 0.1$ was reduced by nearly 82% in the IR-assisted mode. The experimental drying curves also indicated a higher drying rate for the integrated infrared mode than for hot air drying at any given drying time and temperature. In the drying process, when the product is exposed to an infrared heater, the heat impinges on the sample surface and penetrates into the material. The increased molecular vibration due to absorption of radiation generates heat simultaneously at the surface and in the inner layers of the sample. The rapid heating of the material increased the rate of water removal.[3,5] As shown in Fig. 3, a constant rate period was not observed in the range of air drying temperatures studied. Drying rate decreased continuously with time as moisture content fell. Therefore, the entire drying process occurred in the falling rate period, during which internal molecular diffusion is the predominant mechanism of mass transfer.[25,26] Infrared dehydrated samples presented higher drying rates than those corresponding to convective dehydration; in particular, samples dehydrated at 60°C/800 kW and 50°C/800 kW. In infrared assisted air drying, the power density can be six to ten times higher than that in convective drying with hot air and it therefore generates a high rate of liquid evaporation.[27] Thus, application of combined infrared and conventional convective dehydration is considered to be more efficient than radiation or convective drying alone, because of a synergistic effect.[28] These experimental results are consistent with those reported in literature for

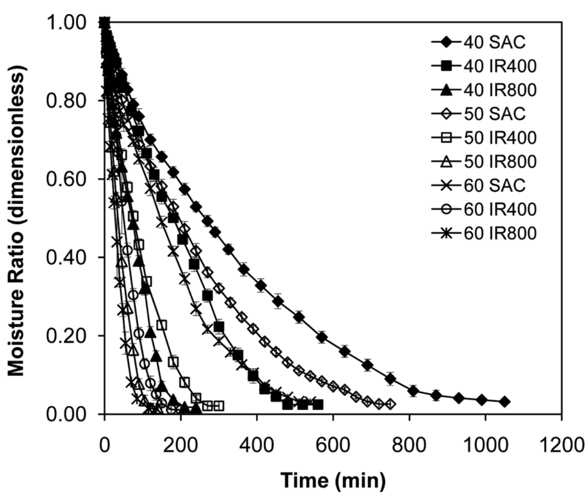

FIG. 2. Experimental drying curves of murta berry under convective and combined convective-infrared drying conditions.

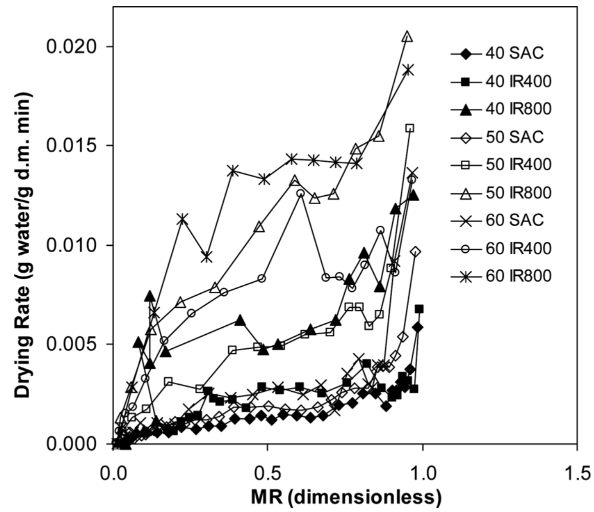

FIG. 3. Experimental drying rates curves of murta berry under convective and combined convective-infrared drying conditions.

infrared as well as for hot air drying technologies. For example, in the case of dehydration of figs,[15] berberies fruits,[29] apples,[5] carrots and potatoes,[30] longan,[3] and onion.[25]

Effect of Infrared Radiation and Drying Temperature on D_{eff}

The estimated effective moisture diffusivities obtained when applying Eq. (4) for different drying conditions are presented in Table 2. Regarding convective air drying, effective moisture diffusivity increased with temperature, the values were found to vary from 7.59×10^{-10} to $44.18 \times 10^{-10}\, m^2/s$ in the range of 40 to 60°C. For the infrared assisted air drying in the same temperature range, the values of effective moisture diffusivity varied from 11.34×10^{-10} to $80.43 \times 10^{-10}\, m^2/s$ and 15.38×10^{-10} to $85.41 \times 10^{-10}\, m^2/s$ for 400 W and 800 W, respectively. These values are comparable with those reported for prunes (4.3×10^{-10}–$7.6 \times 10^{-10}\, m^2/s$, 50–70°C[31]), berberis (3.32×10^{-9}–$9.0 \times 10^{-10}\, m^2/s$, 50–70°C[29]), pineapple rings (4.6×10^{-10}–$16.3 \times 10^{-10}\, m^2/s$, 40–60°C, 1-5 kW/m²[4]), and longan (7.01×10^{-11}–$6.68 \times 10^{-10}\, m^2/s$, 40–80°C, 300–700 W[3]). Moreover, several works reported that moisture diffusivities under infrared conditions were higher compared to those of convective drying.[26,31,32] An activation energy (E_a) was calculated by plotting ln D_{eff} versus the reciprocal of the absolute drying air temperature (Eq. (4)).

Although the absolute temperature in Eq. (4) corresponds theoretically to temperature of the murta berry, for calculation purposes the drying air temperature was used. It was assumed that the murta berries rapidly reached the drying air temperature only within a few minutes after drying began. During infrared heating of the moist murta

TABLE 2
Effective moisture diffusivity of murta berry during convective and combined convective-infrared drying

	Convective		Convective-Infrared 400 W		Convective-Infrared 800 W	
Temperature (°C)	D_{eff} x10^{-10} (m^2/s)	r^2	D_{eff} x10^{-10} (m^2/s)	r^2	D_{eff} x10^{-10} (m^2/s)	r^2
40	7.59 ± 1.65^a	0.99	11.34 ± 1.56^a	0.98	15.38 ± 1.79^a	0.98
50	16.96 ± 1.98^b	0.93	32.32 ± 1.51^b	0.97	60.04 ± 1.33^b	0.98
60	44.18 ± 1.55^b	0.95	80.43 ± 2.56^c	0.97	85.41 ± 1.87^b	0.97

Different superscript letters for the same column indicate that the D_{eff} values are significantly different (p-value <0.05).

materials, IR radiation impinged on the exposed material and penetrated it. Radiation energy is readily converted into heat and the murta berries exposed to IR radiation are intensely heated. Temperature gradient inside the fruits fell almost to zero within a short period.[33] The values of activation energy were found to be 81.04 kJ mol^{-1}, 90.23 kJ mol^{-1}, and 79.40 kJ mol^{-1} for convective drying, convective-infrared 400 W, and convective-infrared 800 W, respectively. Infrared heating offers many advantages over conventional drying under similar drying conditions. Since E_a is the energy barrier to activate water diffusion, as the infrared radiation increased the energy of the drying process also increased. Thus, the lower value of E_a (79.40 kJ mol^{-1} at 800 W) resulted from an increase in the average energy of water molecules, which took part in the mass transfer process during dehydration under this particular condition.[34] The reported activation energy values obtained when infrared drying was applied were comparable with those informed in previous works for berberies fruits[29] and rice,[32] but higher than those reported for olive husk[33] and grape by-products.[35]

Mathematical Modeling of Drying Curves: Kinetic Parameters and Statistical Analysis

Table 3 shows the average values of the kinetic and empirical parameters k_i(i = 1, 2 . . . 9), n_i (i = 1, 2 . . . 12), α and β, obtained for all the selected models. As in the case of effective moisture diffusivities, a similar tendency was observed for each of these kinetic parameters, except for k_9. It was noted that an increase in drying air temperature as well as infrared power showed an increase in these values. Results indicated that kinetic parameters are dependent on drying temperature as well as on infrared conditions (p-value <0.05). Regarding empirical parameters, n_1, n_2, n_6, n_7, n_{12} and α showed dependence on temperature and infrared conditions (p-value <0.05). The kinetic parameters that did not show any trend under the applied drying conditions probably depended on the characteristics of the tissue as well as on other external variables such as initial moisture content, shape and size of product, presence of skin, and others.[13]

The shape parameter (α) in the Weibull equation, which is related to the velocity of the mass transfer at the beginning (e.g., the lower the α value, the faster the drying rate at the beginning) showed a clear trend when applying convective drying and infrared drying at 400 W. It presented an increase with increasing air drying temperature in the mentioned drying modes. However, at 800 W this trend was not observed. Regarding the scale parameter (β), which represents a kinetic reaction constant, a decrease was noted as air temperature increased. Comparable results have been reported in other studies.[13,25]

The statistical tests (SSE, RMSE, and χ^2) performed on the proposed models for each drying conditions evaluated the goodness of fit on experimental data and have been used by other researchers for food drying analysis.[1,13] According to these results (data not shown), the models that best fitted the experimental data, considering the statistical tests applied, were Midilli-Kuçuk (SSE = 0.0003, RMSE = 0.0174, and $\chi^2 = 0.0003$), followed by Logarithmic (SSE = 0.0003, RMSE = 0.02010, and $\chi^2 = 0.0004$). The mentioned models were the mathematical expressions that showed the best statistical fit of the experimental moisture values for all drying conditions.[28] Therefore, in Fig. 4 the experimental drying data as well as the predicted drying behavior estimated by these models (Logarithmic and Midilli-Kuçuk) are shown. These two models can be successfully applied to optimize this integrated drying technology (convective + infrared) in order to obtain the desired final product.

Energy Consumption

Figure 5 shows the energy consumption for convective dehydration as well as for infrared-convective dehydration of murta samples. During convective dehydration, an increase in the drying air temperature caused a reduction in drying time, thus lowering the energy consumption. In the combined method of drying, as the infrared wavelengths are in the range of wavelengths that can be absorbed by water, absorption of these waves by the moisture in murta fruits and vibration of the water molecules generate heat within the product and largely eliminate

TABLE 3
Kinetics and empirical parameters of the selected models used to simulate murta berry drying curves

		Convective			Convective-Infrared 400 W			Convective-Infrared 800 W		
Model/Parameter		40°C	50°C	60°C	40°C	50°C	60°C	40°C	50°C	60°C
Page	n_1	0.9035	1.0732	1.0863	0.8794	0.9872	1.1577	0.8608	1.2303	1.0844
	k_1	0.0052	0.0033	0.0090	0.0085	0.0116	0.0131	0.0123	0.0064	0.0022
Modified Page	n_2	0.9035	1.0732	1.0863	0.8794	0.9872	1.1577	0.8608	1.2303	1.0844
	k_2	0.0030	0.0083	0.0131	0.0044	0.0110	0.0237	0.0060	0.0165	0.0293
Logarithmic	n_3	−0.0622	−0.2930	−0.1970	−0.0885	−0.1070	−0.1170	−0.1140	−0.1430	−0.0059
	n_4	1.0400	1.2900	1.1800	1.0400	1.0800	1.1200	1.0600	1.1800	1.0600
	k_3	0.0024	0.0029	0.0083	0.0031	0.0079	0.0178	0.0040	0.0125	0.0249
Two Terms	n_5	0.4860	0.5230	0.5160	0.4820	0.4960	0.5230	0.4800	0.5470	0.5100
	k_4	0.0028	0.0047	0.0121	0.0038	0.0100	0.0230	0.0052	0.0167	0.0283
	n_6	0.4980	0.5100	0.5020	0.4900	0.5000	0.5110	0.4870	0.5210	0.5040
	k_5	0.0028	0.0047	0.0121	0.0038	0.0100	0.0230	0.0052	0.0167	0.0283
Modified	n_7	0.3220	0.3470	0.3420	0.3180	0.3290	0.3470	0.3170	0.3630	0.3380
Henderson-Pabis	k_6	0.0027	0.0047	0.0121	0.0038	0.0100	0.0230	0.0052	0.0167	0.0283
	n_8	0.3320	0.3470	0.3420	0.3280	0.3360	0.3480	0.3260	0.3580	0.3420
	k_7	0.0027	0.0047	0.0121	0.0038	0.0100	0.0230	0.0052	0.0167	0.0283
	n_9	0.3300	0.3390	0.3330	0.3250	0.3320	0.3390	0.3230	0.3460	0.3350
	k_8	0.0027	0.0047	0.0121	0.0038	0.0100	0.0230	0.0052	0.01670	0.0283
Midili-Kucuk	n_{10}	0.9793	0.9686	0.9597	0.9647	0.9690	0.9810	0.9405	0.9672	0.9662
	n_{11}	0.9734	1.2706	1.1740	0.9588	1.0523	1.1592	1.0609	1.4219	1.1828
	k_9	0.0029	0.0009	0.0046	0.0042	0.0069	0.0110	0.0033	0.0025	0.0136
	n_{12} $(x10^{-5})$	−6.7379	−12.9040	−33.3220	−10.8160	−21.1710	−30.8980	−11.2990	−5.4791	−11.1990
Weibull	α	0.9035	1.0732	1.0863	0.8794	0.9872	1.1577	0.8608	1.2303	1.0844
	β	337.77	203.86	76.36	226.14	90.94	42.12	165.98	60.67	34.07

Different letters in the same line indicate that the values are significantly different (p-value <0.05).

problems related to heat conduction and surface layer drying, resulting in greater reduction of drying time, thus decreasing even more the energy consumption.[23] In the combined convective-infrared drying, heat transfer is simultaneously achieved by both convection and radiation, which accelerates the drying process. Results of analysis showed that minimum energy requirement for drying murta was 5.23 kW h at 60°C and 0.4 kW. Comparable results were reported in previous investigations.[23,36]

Quality Parameters: Surface Color and Total Phenolic Content

Color, an important sensorial parameter in fruit analysis, suffers certain modifications during the drying process.[26] Moreover, color of the final product is dependent on the type of drying method employed. The browning reaction that occurred during drying of the fruit samples has a significant impact on color of the final dried product.[31] The color variation of fresh murta due to processing is shown in Table 4. From the point of view of color coordinates a^*, b^*, and L^*, there are significant differences between the fresh and the dried samples only in a^* and b^* parameters (p-value <0.05). Both coordinates a^* (greenness-redness) and b^* (blueness-yellowness) presented a decrease compared to the fresh samples. The decrease in a^* and b^* values denoted a more green-blue chroma, which is indicative of browning reactions.[1] Maillard reaction and enzymatic browning reaction are often considered as the prevalent contributing factor to this change in color.[31] Comparable results were obtained when processing different foods by means of infrared drying like red pepper,[37] carrot and garlic,[38] orange peel,[39] and apples.[40]

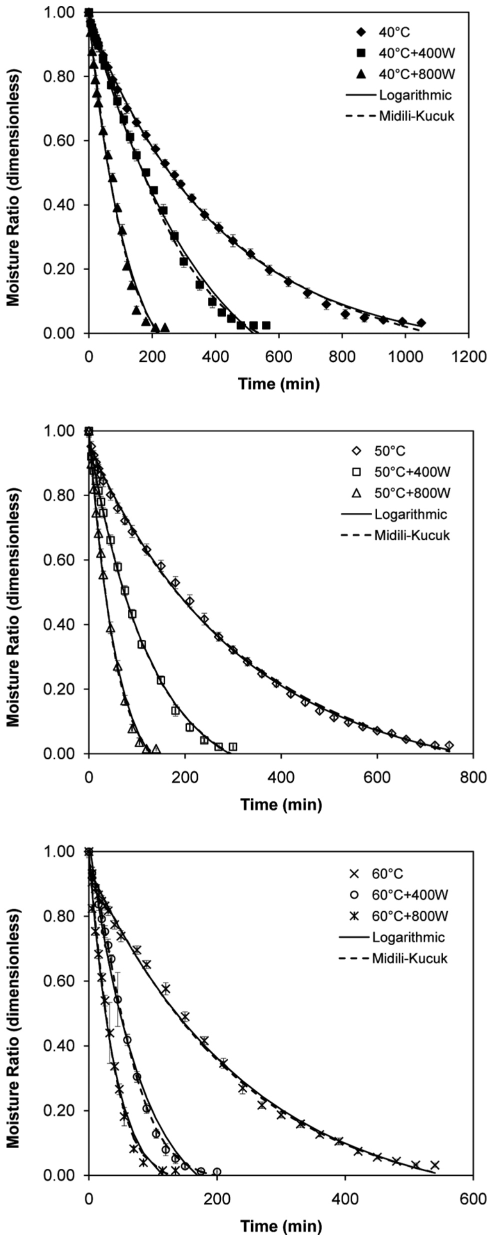

FIG. 4. Comparison between experimental and estimated values of moisture ratio (by Midilli-Kuçuk and Logarithmic) of murta berry under convective and combined convective-infrared drying conditions.

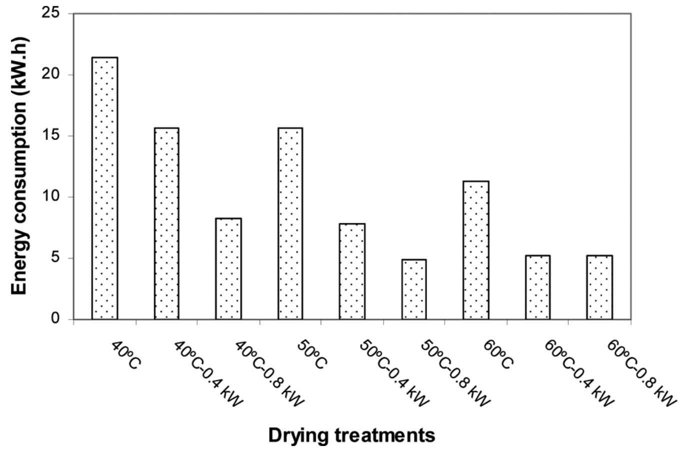

FIG. 5. Energy consumption of murta berry under convective and combined convective-infrared drying conditions ($X_f = 0.105$ g water/g d.m.).

In general, the L* parameter did not show significant differences among samples (p-value <0.05) with the exception of samples dried at 40°C/800 W that presented the lower value of L* compared to control samples. These results indicated that the brightness coordinate L*, which measures the whiteness of the fruit, faded due to changes in surface texture under this particular condition (40°C/800 W). Changes in total color difference (ΔE), a very important quantity to determine, since it represents the overall color change of the sample with respect to a standard reference,[41] are brought about by simultaneous heat and mass transfer occurring at the surface of the murta berries and depended on drying conditions.[1] The modifications of ΔE were mainly due to changes in the chromatic parameters a* and b*. The effect of drying conditions on total color difference (ΔE) is also shown in Table 4. For all thermal treatments, high significant differences were observed in dried murta since $\Delta E > 20.5$ was verified.[40,41] An increase in the drying temperature when processing without infrared resulted in an increase in ΔE. This could be explained due to an increase in the kinetic reaction rate of the browning process that resulted from the presence of reducing sugars and amino acids in the material being dehydrated. When observing the effect of convective-infrared drying on ΔE, for a given drying temperature an increase in the infrared radiation intensity resulted in a decrease of ΔE, except at 40°C, where longer drying times associated with lower drying temperatures would intensify the effect of higher radiation energy on browning reaction. The effectiveness of drying in terms of product color quality was increased by the application of the combined convective-infrared method. The color of the food surface is the first quality parameter evaluated by consumers and is critical in the acceptance of the product. Since ΔE is characterized by a high correlation with the external visual color of the fruit, Fig. 6 presents the images of fresh as well as dehydrated murta berries under all studied conditions. It can be observed that all treatments modified the initial color of murta fruits, indicating browning as was discussed previously.

The beneficial health properties of murta extracts have been attributed to the presence of polyphenols.[42] Phenolic compounds, ubiquitous in plants, are an essential part of the human diet, and are of considerable interest due to their antioxidant properties.[43] The initial TPC of murta was 4.35 ± 0.12 g gallic acid/100 g dried murta, which

TABLE 4
Quality parameters of murta berry under convective and convective-infrared drying conditions

T (°C)/IR (W)	L*	a*	b*	TPC (mg GA/100 g dry matter)	△E
Control	43.49 ± 0.89^{c}	53.02 ± 3.18^{c}	34.22 ± 1.96^{c}	4.35 ± 0.12^{a}	–
40/0	50.62 ± 4.77^{c}	34.32 ± 4.63^{d}	23.47 ± 2.05^{d}	2.17 ± 0.10^{b}	23.3 ± 2.95^{de}
40/400	47.25 ± 4.75^{c}	30.66 ± 2.37^{de}	25.94 ± 9.64^{cd}	3.27 ± 0.09^{c}	25.5 ± 4.71^{def}
40/800	35.55 ± 5.30^{d}	26.54 ± 3.71^{e}	17.04 ± 2.68^{d}	3.74 ± 0.04^{d}	32.7 ± 5.60^{f}
50/0	49.99 ± 7.48^{c}	31.84 ± 0.88^{de}	24.86 ± 8.49^{d}	1.40 ± 0.05^{e}	25.8 ± 0.48^{def}
50/400	45.22 ± 3.54^{c}	30.66 ± 4.82^{de}	24.46 ± 6.03^{d}	2.93 ± 0.08^{f}	24.9 ± 6.44^{def}
50/800	47.68 ± 1.45^{c}	35.29 ± 2.45^{d}	24.85 ± 1.37^{d}	3.41 ± 0.14^{c}	20.5 ± 2.48^{d}
60/0	43.33 ± 3.18^{c}	25.66 ± 5.29^{e}	20.91 ± 4.62^{d}	0.96 ± 0.04^{h}	30.8 ± 5.11^{ef}
60/400	48.15 ± 2.64^{c}	29.87 ± 5.64^{de}	22.55 ± 4.97^{d}	1.77 ± 0.04^{i}	26.6 ± 6.69^{def}
60/800	45.54 ± 5.63^{c}	28.12 ± 3.26^{de}	22.22 ± 4.02^{d}	2.22 ± 0.07^{b}	28.2 ± 3.91^{def}

Different superscript letters for the same column indicate that the parameters are significantly different (p-value <0.05).

according to Rufino et al. (2010) is classified into medium category.[44] This value is comparable with those reported in some previous works,[12,42] but lower compared to other reported values.[44] Significant differences in contents of phenolic compounds were positively correlated with cultivar and growing region as well as with the type of solvent extraction.[45] In addition, thermal processing has been reported to have both adverse and favorable effects on TPC.[46–48]

When analyzing convective drying without IR processing, it can be observed that the retention of intact polyphenolics is highly dependent on the rates of dehydration (p-value <0.05). Thus, dehydration of murta at 60°C led to the lower value of TPC. Among processed samples, and for a constant drying temperature, an increase in infrared power showed higher values of TPC content in dried fruits. In particular, samples processed at 40°C and 800 W resulted in extracts containing the highest TPC (e.g., 3.74 g GA/g dry sample). These results could indicate that infrared drying contributed to enhancement in retention of the amount of total phenolics extracted from the samples. Plant phenolics are sequestered within vacuoles in healthy intact plant tissue to protect them from oxidation, and only on physical breakdown of the plant tissue structures are phenolics exposed to oxygen.[46] In addition, the disruption of cell walls may also activate the release of oxidative and hydrolytic enzymes that would destroy the antioxidants compounds in the product. However, high temperature involved during the drying process would deactivate these enzymes and avoid the loss of phenolic compounds.[48] Our observations on TPC during IR-assisted drying could be attributed to the fact that the surface temperature of the murta berries quickly rose during heating and the water vapor formed inside the fruit forced its way through the cellular walls, which caused the development of large pores within the cell wall materials.[49] This facilitated the liberation of the phenolic compounds, revealing that the infrared drying process could enhance the functional values of murta berries by increasing the antioxidant capacity of dried products.[48] These preliminary observations provided the basis for further examination of the suitability of polyphenol-enriched extracts from murta as nutritional or medicinal supplements with potential human health benefits.

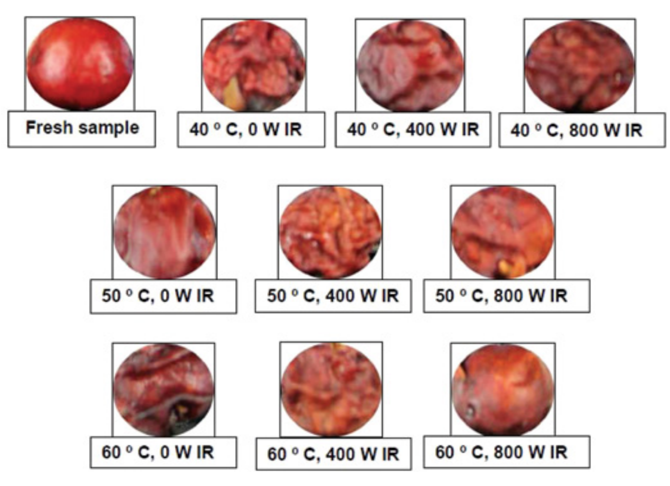

FIG. 6. Images of murta berry under convective and combined convective-infrared drying conditions (color figure available online).

CONCLUSIONS

During the combined infrared-convective drying of murta berries, infrared power (400-800 W) significantly influenced drying rate and reduced total drying time compared to convective drying. Effective moisture diffusivities showed dependence on temperature as well as on infrared power. The maximum effective moisture diffusivity was observed at 60°C/800 W. Experimental drying curves were best described by the Midilli-Kuçuk and logarithmic models that presented the best fit based on statistical tests.

Surface color of the murta berries showed significant variation during the drying process; both chromatic parameters a* and b* decreased compared to fresh samples, denoting browning reactions. Total color difference of $\Delta E > 20$ was observed during dehydration. When analyzing convective drying without IR heating, a highly dependent retention of TPC on dehydration rates was observed; at higher drying temperature lower TPC was found. However, at a constant drying temperature, an increase in infrared power increased TPC (e.g., at 40°C from 2.17 to 3.74 g GA/g d. m. from 0 to 800 W). Altogether, advantages of combined infrared-convective drying over pure convective drying were observed in this work. Energy consumption decreased as air drying temperature increased for convective dehydration and for increasing infrared power in the combined method. Minimum energy consumption was achieved at 60°C/0.4 kW. There is a drastic reduction in drying time, thus in energy consumption in the convective-infrared mode of drying. Degradation in quality of the dried product can be minimized if a proper level of radiation intensity and air temperature is carefully selected for the dehydration process. A compromise decision is required in order to simultaneously optimize process efficiency and final product quality; 40°C/800 W could be an option.

NOMENCLATURE

D_{eff}	Effective moisture diffusivity (m^2/s)
D_o	Pre-exponential factor of the Arrhenius equation (m^2/s)
E_a	Activation energy (kJ/mol)
j	Number of terms
k	Kinetic parameter (1/min)
n	Empirical parameters (dimensionless)
N	Number of data values
m	Number of constants
r	Mean radius of the sphere (m)
R	Universal gas constant (8.314 J/mol · K)
t	Drying time (s)
T	Absolute temperature (K)
X_{wt}	Moisture content (g water/g d.m.)
X_{wo}	Initial moisture content (g water/g d.m.)
X_{wo}	Equilibrium moisture content (g water/g d.m.)
z	Spatial dimension (m)

Greek Letters

α	Shape parameter of Weibull model
β	Scale parameter of Weibull model (min)

Subscripts

cal	Calculated
exp	Experimental
i	Number of terms

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