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Quality properties, mass transfer characteristics and energy consumption during shortwave infrared radiation drying of tomato

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RESEARCH ARTICLE

Abstract

The influence of infrared radiation intensity (1,830, 2,640 and 3,165 W/m^2) and air velocity (1.0, 1.5 and 2.0 m/s) on product quality, drying behaviour of tomato and energy consumption were investigated. Five analytical models were used to investigate mass transfer characteristics during infrared drying of tomato slices. The drying time and specific energy consumption varied between 141 and 246 min, and 10.04 and 15.13 MJ/kg water, respectively, and were significantly influenced by infrared radiation intensity and air velocity. Effective moisture diffusivity ranged from 3.89×10^{-7} to 6.67×10^{-7} m^2/s and was significantly affected by the process variables. Vitamin C content decreased, while lycopene content increased during drying. Total colour change varied between 7.92 and 10.87 for all drying conditions. The logarithmic model gave the best predictions for the drying characteristics of tomato slices for all treatments. Some drying conditions had quite similar results with respect to the operational and quality features.

Keywords: tomato, infrared drying, mass transfer, energy consumption, moisture diffusivity

1. Introduction

Tomato (*Lycopersicon esculentum* L.) plays an important role in human nutrition as it is a rich source of minerals, vitamins, organic acids and dietary fibre (Rajkumar *et al.*, 2007). It is one of the world's most commercially produced and widely consumed vegetables. In addition, tomato is processed in different product forms (frozen, tomato paste, ketchup, pickles, dried, etc.). China (31%), the USA (8%), India (8%) and Turkey (7%) are the largest tomato producing countries (FAO, 2010).

Tomato is a rich source of ascorbic acid, pro-vitamin A and minerals, particularly potassium, compared to many other fruits and vegetables (Akanbi and Oludemi, 2004). It is also the main source of lycopene, which is one of 600 carotenoids and responsible for the red colour of tomato, red pepper, watermelon and pink grapefruit (Goula and Adamopoulos, 2005). Recent studies have shown that lycopene intake reduces the risk of some types of cancer and plays an important role in human health (Brandt *et al.*, 2006). Lycopene is one of the most potent antioxidants, with a singlet-oxygen-quenching ability twice as high as that of β-carotene and 10 times higher than that of α-tocopherol (DiMascio *et al.*, 1989).

Although tomato is generally preferred to be consumed in fresh form, developments in food technology have caused an increase in demand for dried tomato, which is used as a component for fast foods, ready-to-eat foods and dressings (Doymaz, 2007). Hot air drying, sun drying, solar tunnel drying, microwave drying and freeze drying are the most common methods used to dry tomatoes. Several experimental studies have been published to determine the effects of drying methods on dried food quality, drying behaviour and consumed energy under different drying conditions and dryers, and to define a mathematical model of mass transfer for tomato drying. For example, studies that used hot air dryers (Doymaz, 2007; Marfil *et al.*, 2008), solar tunnel dryers (Sacilik *et al.*, 2006), open sun drying and solar sun dryers (Demir and Sacilik, 2010), hot air dryers, solar cabinet dryers, heat pump dryers, microwave drying and freeze drying (Gaware *et al.,* 2010), infrared dryers (Correa *et al.,* 2012) and solar drying (Bagheri *et al.,* 2013) have been published.

Drying not only makes it possible to increase the shelf life of vegetables and fruits, but it is also an important operation employed in fruit and vegetable processing in terms of food quality. However, it requires high energy inputs in industrial applications. Utilisation of electromagnetic energy for the drying of agricultural and food products has gained attention among potential drying technologies in the past ten years due to its fast and homogeneous heating, high energy efficiency and the high quality of the final product (Kocabiyik, 2012). Infrared drying has been the most noticeable among these methods in recent years. The drying characteristics of different fruit, vegetable and grain and their mathematical drying models are still being developed. Drying models are used to generalise drying curves and also to predict drying time of products. However, virtually no information exists on models for thin layer infrared dried tomatoes in the scientific literature.

The objectives of this study were to determine the effects of infrared radiation intensity (IR) and air velocity (v) on the drying behaviour of tomato slices and dried tomato quality; to evaluate the suitability of the experimental data for the various thin layer drying models; to find the effective moisture diffusivities of the infrared dried tomato slices and to investigate the similarity of drying conditions.

2. Materials and methods

Sample preparation

Tomato samples (var. Toro F1) at full ripening stage were acquired from a local grower in Canakkale, Turkey and stored in a refrigerator at 4±1 °C until the drying experiments. The initial moisture content of the raw tomato was 9.0 kg water/kg dry matter (DM), which was determined in triplicate using a convection oven at 105 °C for 5 h (AOAC, 2000).

Experimental set-up and drying procedures

The schematic diagram of the drying system and instrumentation used to conduct the experiments were presented in Kocabiyik *et al.* (2014a,b). The dryer consisted of three main units, namely a drying chamber, controlling system and data recording system with a computer. The drying chamber of 0.7×0.4×0.5 m was made from a stainless steel sheet of 2 mm thickness. The dryer was equipped with a shortwave infrared emitter (1.0-1.4 μm) with golden reflector (Heraeus-Noblelight, Hanau, Germany) with a maximum power of 1,500 W in the drying chamber. The distance between the emitter and drying surface was maintained at a constant 0.2 m throughout the experiments. Infrared radiation intensity could be varied by regulating the voltage of the emitter through a variac. Infrared radiation intensity was controlled and measured by a pyranometer with a spectral range of 0.3-2.8 μm and with a sensitivity of 7 to 14 μV/W/m^2 (CMP 11; Kipp&Zonen, Delft, the Netherlands).

The drying experiments were conducted at an IR of 1,830, 2,640 and 3,165 W/m^2 and v of 1.0, 1.5 and 2.0 m/s, respectively. All experiments were replicated two times. Inlet air temperature for all drying experiment was 30±1 °C and not heated. Before a drying experiment, the dryer was run idle for about 10 min to achieve the pre-set experiment drying conditions. The raw tomato samples were cut longitudinally into eight equal slices (thickness of 8.0±1.3 mm) and uniformly placed on the Teflon-coated wire mesh tray (0.4×0.3 m) in a thin layer form (loading rate of 4.0 kg/m^2) and without any pre-treatment. To evaluate the quality features of the tomato after the drying process, ten tomato slices were selected and numbered.

The mass loss of tomato slices on the tray was measured by a digital balance with a measurement range of 0-2, 200 g and with an accuracy of ±0.01 g, and recorded at 3-min intervals using Balint interface software (Precisa Instrumens AG, Zurich, Switzerland) on a computer during the drying period. The drying continued until a moisture content of 0.136 kg water/kg DM was achieved.

Theoretical basis and moisture diffusivity determination

The dimensionless moisture ratio (MR) of the tomato during drying was obtained by Equation 1.

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (1)$$

where M_t is the moisture content at time t, and M_i and M_e are the initial and equilibrium moisture content, respectively. However, the moisture ratio was simplified by modifying Equation 1 to Sacilik *et al.* (2006):

$$MR = \frac{M_t}{M_i} \quad (2)$$

The mathematical models frequently used to describe the kinetics of the drying processes of agricultural products were fitted to the experimental data of the moisture ratio versus drying time. These models are given in Table 1. Non-linear regression techniques were applied to achieve the specific constants and coefficient of determination (R^2) in each selected model. Statistica 10.0 (StatSoft, Inc. Tulsa OK, USA) was used to perform the nonlinear regression analysis based on the Levenberg-Marquart method. In addition to R^2, the root mean square error (E_{RMS}) and reduced chi-square (χ^2) obtained for these equations were used to compare the relative goodness of fit of the experimental data. The higher the value of R^2 and the lower the values of

Table 1. Mathematical models applied to the drying curves.

Name	Model equation
Newton	*MR* = exp(-kt)
Page	*MR* = exp(-kt^n)
Henderson and Pabis	*MR* = a exp(-kt)
Logarithmic	*MR* = a exp(-kt) + b
Wang and Singh	*MR* = 1 + at + bt^2

χ^2 and E_{RMS}, the better the goodness of the fit is (Bagheri *et al.*, 2013; Correa *et al.*, 2012; Sacilik *et al.*, 2006). χ^2 and E_{RMS} were calculated according to Equation 3 and Equation 4:

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

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

where $MR_{exp,i}$ is the i^{th} experimental moisture ratio, $MR_{pre,i}$ is the i^{th} predicted moisture ratio, N is the number of observations, and m is the number of constants in the model.

The effective diffusion coefficient (D_{eff}) was determined using Fick's diffusion equation for an infinite slab (Equation 5):

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

where L is the half thickness of slab (m), n is the number of terms of the Fourier series, and t is the drying time (s).

For a long drying period, the diffusion equation can be further simplified by a one-term series (Samadi and Loghmanieh, 2013). Therefore, the equation is rewritten as Equation 6.

$$ln\, MR = ln\,\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}\, t}{4L^2} \tag{6}$$

The effective diffusion coefficient is typically obtained by plotting *lnMR* versus drying time in Equation 6, since the plot gives a straight line with a slope according to Equation 7.

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

Energy consumption determination

Total energy was defined as the sum of the energy consumed by all the devices during the whole drying process, and measured by a digital electricity meter. The specific energy consumption (E_s) of tomato slices during drying was calculated by dividing total energy consumption by evaporated water, and expressed in MJ/kg for unit water evaporated (Durance and Wang, 2002; Wang and Sheng, 2006).

Determination of physical properties

The rehydration ratio (R_e) of dried tomato slices was evaluated by immersing dried slices in distilled water. Approximately 10 g of dried tomato sample was placed in a 100 ml beaker, 50 ml distilled water was added and placed in hot water bath (30 °C) for 3 h (Doymaz, 2007; Durance and Wang, 2002). After rehydration, surface moisture was gently removed with a tissue paper. The mass of rehydrated tomato samples divided by the mass of dried tomato samples was expressed as the rehydration ratio.

The colour of fresh and dried tomato slices was measured using a Minolta CR-400 Chroma Meter (Konica Minolta Sensing, Inc., Osaka, Japan). L^* (lightness/darkness), a^* (redness/greenness) and b^* (yellowness/blueness) colour values of 10 fresh (f) and dried (d) tomato slices were measured in each experiment. It should be noted that these same tomato slices were subject to colour measurement after drying. The total colour change (ΔE) was calculated as in Equation 8.

$$\Delta E = \sqrt{(L_f - L_d)^2 + (a_f - a_d)^2 + (b_f - b_d)^2} \tag{8}$$

Determination of vitamin C, lycopene and β-carotene

Vitamin C, lycopene and β-carotene content of raw and dried tomato were determined according to Kocabiyik *et al.* (2014a). Approximately 10 g of dried tomato was homogenised (Arzum AR-132 mixset; Arzum, Istanbul, Turkey) for 30 s at high rotation. For vitamin C analysis, 0.5 g DM of homogenised tomato sample was weighed into an aluminium foil-wrapped centrifuge tube and 20 ml of 2.5% metaphosphoric acid was added. The contents were shaken at room temperature on an orbital shaker (Unimax 2010; Heidolph, Schwabach, Germany) for 30 min and centrifuged at 4,495×*g* at 4 °C for 10 min. 2 ml supernatant was then pipetted into a 10 ml flask and brought to volume with 2.5% metaphosphoric acid (Sigma-Aldrich, Munich, Germany). The contents were filtered through a 0.45 µm membrane filter and transferred to an amber HPLC vial. The analysis was performed using an Agilent HPLC series 1200 (Agilent, Waldbronn, Germany). The mobile phase consisted of 2% KH_2PO_4 (Sigma-Aldrich) adjusted to pH 2.4 with ortho-phosphoric acid. The separation was carried out with a Zorbax Eclipse XDB-C18 column (250 mm, 4.6 mm i.d. and 5 µm particle size) (Agilent) operated at 25 °C. The isocratic flow rate was set at 0.5 ml/min, and the injection volume was 10 µl. UV detection wavelength was set at 244 nm.

For lycopene and β-carotene analysis, 15 ml of deionised water was added to 1 g (dry basis) homogenised tomato sample and incubated at 30 °C in a water bath for 30 min. The tomato-water mixture was shaken at room temperature on an orbital shaker for 1 h after which 25 ml of hexane:acetone:ethanol (2:1:1, v/v/v) was added. The new content was further shaken for another 30 min and the extracts centrifuged at 4,495×*g* at 4 °C for 10 min or until the separation of aqueous and organic phase was achieved. 1 ml of supernatant from the hexane layer was transferred to a rotary flask and evaporated to dryness at 40 °C. The residue was redissolved in tetrahydrofuran and mobile phase (50:50, v/v) and filtered through a 0.45 μm membrane filter into an autosampler vial for HPLC analysis. The mobile phase consisted of methyl tert-butyl ether:methanol:ethyl acetate. The composition of the eluents was 30:60:10 (0-10 min) and linearly changed to 45:43:12 (10-15 min). Elution continued isocratically with 45:43:12 (15-24 min). The separation was carried out with a YMC C30 column (250 mm, 4.6 mm i.d. and 5-μm particle size) (YMC Inc.,Wilmington, NC, USA) operated at 40 °C. The flow rate was 1 ml/min throughout the analysis. The sample injection volume was 5 μl. The absorbance was measured to be 450 nm for β-carotene and 472 nm for lycopene.

Statistical analysis

ANOVA analysis was performed using Minitab R16 statistical software (StatSoft, Inc., Tulsa OK, USA) to determine the contribution of the independent variables (IR and v) on drying time, specific energy consumption, effective moisture diffusivity and the quality of dried tomato using a significance level of 5%. Tukey's test was performed at a confidence level of 5% for mean separation. Also, functional similarity values such as the operation features of drying condition, physical features and nutritional features of dried tomato were used to produce a dendrogram (cluster analysis) which explained the relationship among the drying methods.

3. Results and discussion

Drying kinetics and energy consumption

The effects of infrared radiation intensity (IR) and air velocity (v) (1.5 m/s) on the moisture ratio as function of drying time are shown in Figure 1A. The effects of v and IR (1,830 W/m^2) on the moisture ratio as function of drying time are shown in Figure 1B. The moisture ratio decreased continuously with drying time. At the other air velocities (1.0 and 2.0 m/s) and infrared radiation intensities (2,640 and 3,165 W/m^2), the effects of IR and v on various moisture ratio with drying time showed a similar trend.

The drying time required to reduce the moisture content from 9.00 to the safe storage level of 0.136 kg water/kg DM ranged between 141 and 246 min for all the drying conditions. The drying time was shortened with increasing IR, while the drying time prolonged with increasing v (Figures 1A and 2). The drying time of the tomato slices increased by 36.7, 10.7 and 14.9% when the air velocity increased from 1.0 to 2.0 m/s at 1,830, 2,640 and 3,165 W/m^2 IR, respectively. In addition, the drying times shortened by 21.7, 27.9 and 34.1% when IR increased from 1,830 to 3,165 W/m^2 at an air velocity of 1.0, 1.5 and 2.0 m/s, respectively. Because of non-heated inlet air and the increasing amount of air flow with increasing air velocity, surface cooling effect was occurred during the drying period. Therefore, drying time at higher air velocities were longer than that of lower ones. The dependence of the drying time of tomato slices on the IR and v can be represented by Equation 9.

$$\text{Drying time} = 239.77 - 0.0449\text{IR} + 35v \quad R^2 = 0.896 \qquad (9)$$

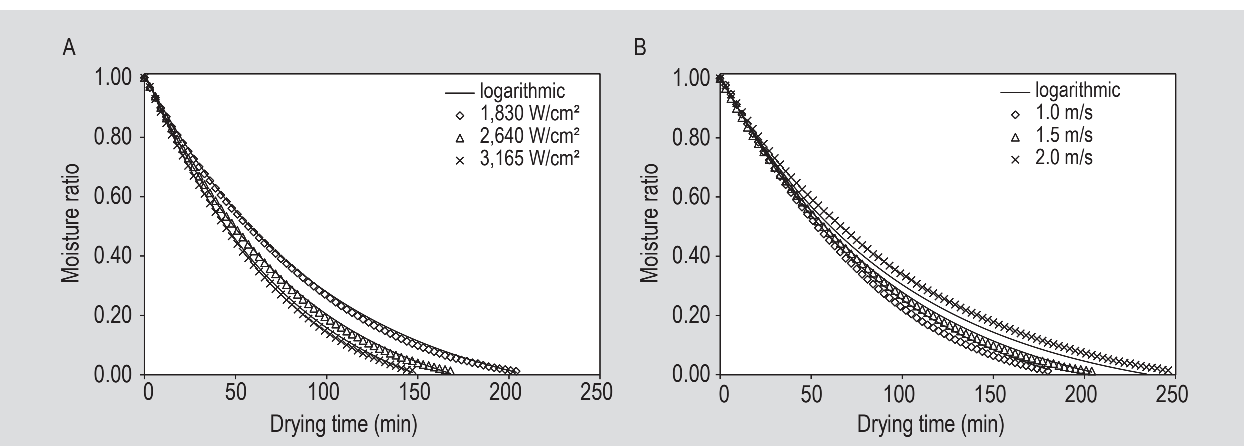

Figure 1. Variation of moisture ratio with drying time at (A) different infrared radiation intensity at 1.5 m/s air velocity and (B) different air velocity at 1,830 W/m² infrared radiation intensity.

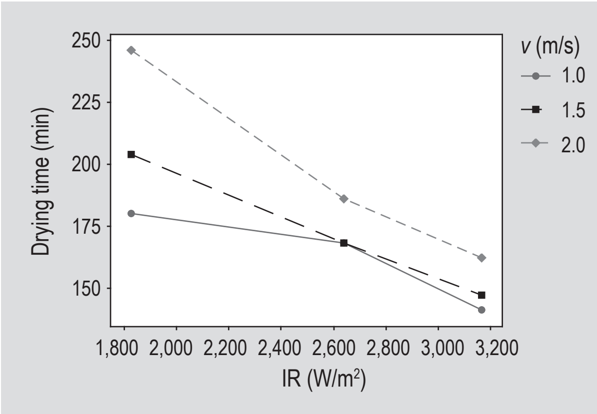

Figure 2. Variation of drying time with infrared radiation intensity (IR) and air velocity (*v*).

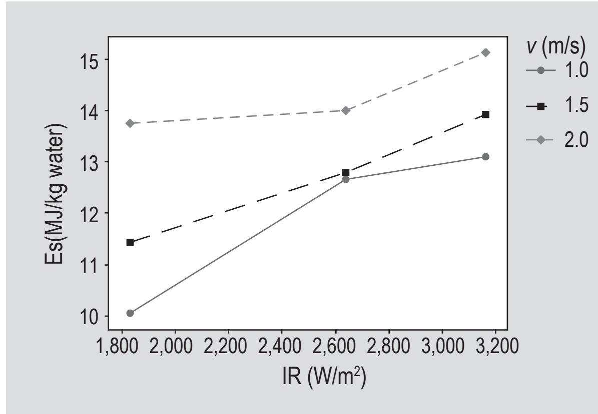

Figure 3. Variation of specific energy consumption with infrared radiation intensity (IR) and air velocity (*v*).

Sacilik *et al.* (2006) compared the performance of a solar tunnel dryer with open sun drying and reported that the drying time required to reduce the moisture content of organic tomatoes to 11.50% (wb) ranged between 82 h (4,920 min) and 96 h (5,760 min) for solar tunnel drying and 106 h (6,360 min) and 120 h (7,200 min) for open sun drying. Doymaz (2007) used different air temperatures (50, 60, 65 and 70 °C) and air velocities (1.5 m/s) for the drying of tomato slices in a hot air dryer, and found that the drying time ranged from 1,140 to 2,130 min. Decreasing drying time with increasing infrared power or infrared radiation intensity was also reported by Afzal and Abe (1999) for potatoes, by Sharma *et al.* (2005) and Pathare and Sharma (2006) for onion slices and by Kocabiyik and Tezer (2009) for carrots.

Specific energy consumption values (E_s) varied between 10.04 and 15.13 MJ/kg-evaporated water for all the drying conditions (Figure 3). E_s increased with increasing IR and v. The interaction of IR and v had significant effects on E_s. The combined effects of IR and v on the E_s were defined by Equation 10.

$$E_s = 5.034 + 0.001731IR + 2.36v \qquad R^2 = 0.90 \qquad (10)$$

Validation and comparison of models

The moisture ratios of tomato slices dried in nine different drying conditions were fitted to the five thin layer drying models as given in Table 2. In all drying conditions, R^2, χ^2 and E_{RMS} values for all models varied between 0.9798 and 1.0; 0.000032 and 0.0017511; 0.0017570 and 0.0414166, respectively. As shown in Table 2, the highest R^2 and the lowest χ^2 and E_{RMS} values were found for the logarithmic model under all drying conditions.

To account for the effect of the infrared drying variables on the logarithmic model constants (k, a and b), these constants were analysed against IR and v using multiple regression analysis. The multiple regression analysis on the logarithmic model constants k, a, and b with the process variables resulted in the following relationships: k and a increased with increasing IR, while the same constants decreased with increasing v. Contrary to this, constant b decreased with increasing IR, while the same constant increased with increasing v. The relationships of k, a, and b constants as functions of independent variables were defined by Equation 11, 12 and 13, and shown in Figure 4.

$$k = 7.18\times10^{-3} + 2\times10^{-6} IR - 4.43\times10^{-4} v \qquad (11)$$

$$R^2 = 0.834$$

$$a = 1.18\times10^{-5} + 3.7\times10^{-5} IR - 6.96\times10^{-2} v \qquad (12)$$

$$R^2 = 0.938$$

$$b = -1.7\times10^{-1} - 2.8\times10^{-5} IR + 5.78\times10^{-2} v \qquad (13)$$

$$R^2 = 0.996$$

Effective moisture diffusivity

The determined effective moisture diffusivities (D_{eff}) for different IR and v are shown in Figure 5. The D_{eff} was greatly influenced by the IR and v, and varied in the range of 3.89×10^{-7} to 6.67×10^{-7} m^2/s. The D_{eff} increased with increasing IR, while it decreased with increasing v. The higher radiation intensity caused an increase in effective moisture diffusivity because of the higher mass transfer. Also, because of the increasing amount of air flow with increasing v, surface cooling of the samples during the drying period occurred. Therefore, mass transfer at high air velocity was lower than that of low air velocity. Based on multiple regression analysis, the dependence of D_{eff} of tomato slices on the process variables can be represented by Equation 14.

Table 2. Statistical analysis results and model constants for various drying models.[1]

Model	IR (W/m^2)	*v* (m/s)	R^2	E_{RMS}	χ^2	Model constants
Newton	1,830	1	0.9822	0.03871	0.001523	k=0.01449
		1.5	0.9873	0.03192	0.001033	k=0.01348
		2	0.9921	0.02456	0.00061	k=0.01127
	2,640	1	0.9808	0.04025	0.001649	k=0.01515
		1.5	0.9835	0.03709	0.0014	k=0.01574
		2	0.9871	0.0324	0.001066	k=0.01466
	3,165	1	0.9798	0.04142	0.001751	k=0.01752
		1.5	0.9826	0.03824	0.001492	k=0.01757
		2	0.9853	0.03484	0.001236	k=0.01641
Page	1,830	1	0.9978	0.01375	0.000196	k=0.00498; n=1.24454
		1.5	0.9967	0.01629	0.000273	k=0.00597; n=1.18215
		2	0.9974	0.01409	0.000203	k=0.00616; n=1.13001
	2,640	1	0.9971	0.01572	0.000256	k=0.00512; n=1.25101
		1.5	0.9976	0.01426	0.000211	k=0.00585; n=1.23068
		2	0.9975	0.01422	0.000209	k=0.00629; n=1.19345
	3,165	1	0.9974	0.01486	0.00023	k=0.00584; n=1.26378
		1.5	0.9974	0.0148	0.000228	k=0.00649; n=1.23866
		2	0.9978	0.01343	0.000187	k=0.00656; n=1.21550
Henderson and Pabis	1,830	1	0.9886	0.031	0.000993	k=1.07412; a=0.01557
		1.5	0.9902	0.02801	0.000807	k=1.04993; a=0.01415
		2	0.9939	0.02164	0.00048	k=1.03832; a=0.01171
	2,640	1	0.9872	0.03282	0.001115	k=1.07364; a=0.01627
		1.5	0.989	0.03031	0.000951	k=1.06848; a=0.01682
		2	0.991	0.02709	0.000757	k=1.05777; a=0.01551
	3,165	1	0.9867	0.03351	0.001171	k=1.07567; a=0.01887
		1.5	0.9882	0.0315	0.001033	k=1.06853; a=0.01878
		2	0.9901	0.02848	0.000841	k=1.06437; a=0.01747
Logarithmic	1,830	1	0.9996	0.00587	0.000036	k=0.01100; a=1.18837; b=-0.16405
		1.5	0.9998	0.00432	0.000019	k=0.01035; a=1.14241; b=-0.13859
		2	1	0.00176	0.000003	k=0.00915; a=1.10423; b=-0.10379
	2,640	1	0.9997	0.00532	0.00003	k=0.01108; a=1.20875; b=-0.18798
		1.5	0.9996	0.0056	0.000033	k=0.01201; a=1.17677; b=-0.15670
		2	0.9998	0.00376	0.000015	k=0.01150; a=1.14607; b=-0.13281
	3,165	1	0.9996	0.006	0.000038	k=0.01263; a=1.22529; b=-0.20254
		1.5	0.9997	0.00542	0.000031	k=0.01309; a=1.19162; b=-0.17296
		2	0.9997	0.00495	0.000026	k=0.01273; a=1.16334; b=-0.14467
Wang and Singh	1,830	1	0.9993	0.00746	0.000058	a=-0.01077; b=0.00003
		1.5	0.9976	0.01394	0.0002	a=-0.00999; b=0.00003
		2	0.9947	0.02007	0.000413	a=-0.00843; b=0.00002
	2,640	1	0.9995	0.00658	0.000045	a=-0.01125; b=0.00003
		1.5	0.9992	0.00836	0.000072	a=-0.01170; b=0.00004
		2	0.998	0.01289	0.000171	a=-0.01090; b=0.00003
	3,165	1	0.9997	0.00513	0.000027	a=-0.01305; b=0.00004
		1.5	0.9993	0.00678	0.000048	a=-0.01307; b=0.00004
		2	0.9988	0.00985	0.000101	a=-0.01223; b=0.00004

[1] IR = infrared radiation intensity; *v* = air velocity; E_{RMS} = root mean square error; χ^2 = chi-square.

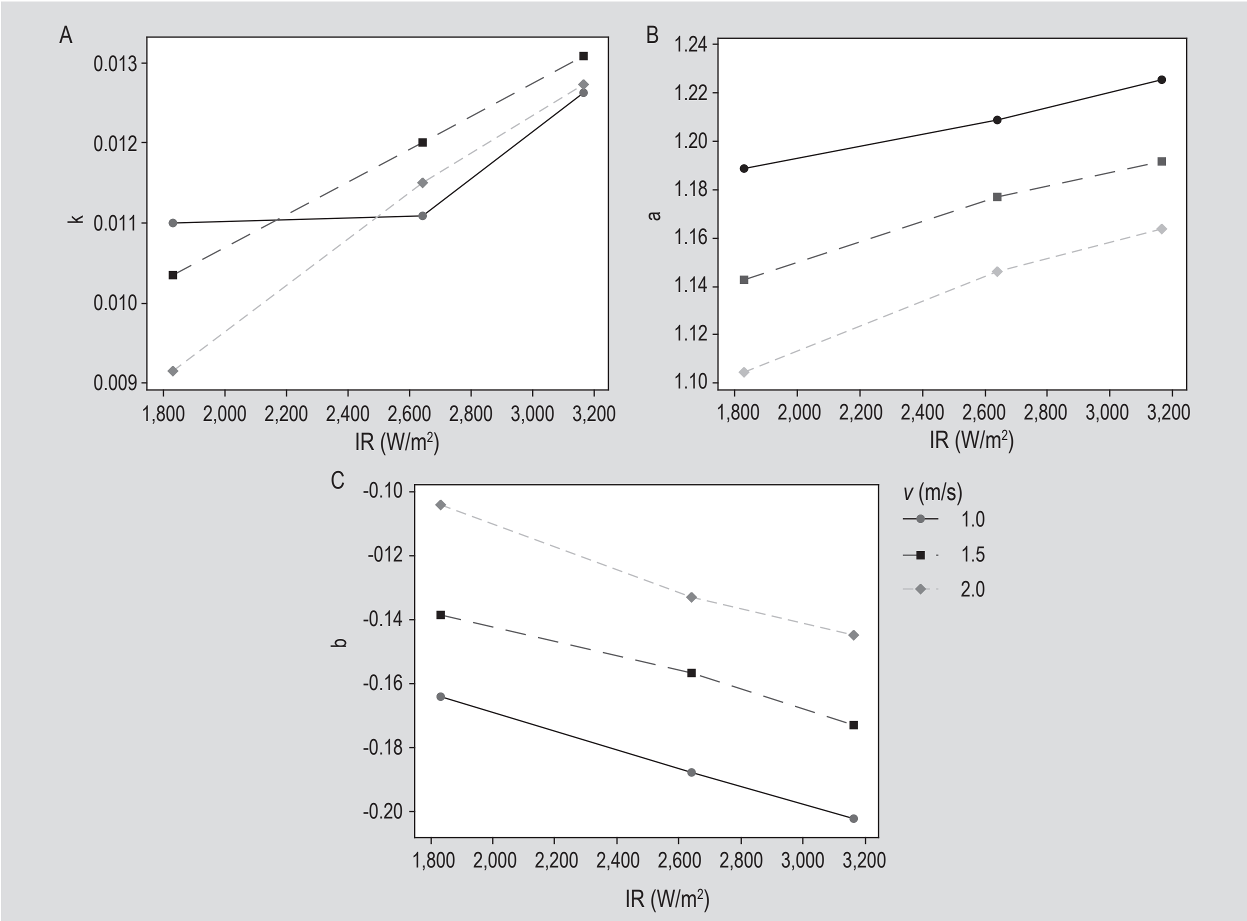

Figure 4. Variation of constants (A) *k*, (B) *a* and (C) *b* with infrared radiation intensity (IR) and air velocity (*v*).

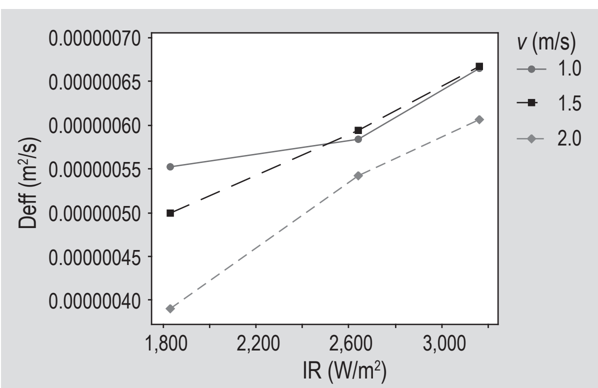

Figure 5. Variation of determined effective moisture diffusivity (D_{eff}) with infrared radiation intensity (IR) and air velocity (*v*).

$$D_{eff} = 3.83\times10^{-7} + 1.24\times10^{-10}\, IR - 8.76\times10^{-8} v \quad (14)$$

$R^2 = 0.894$

For hot air drying Giovanelli *et al.* (2002) reported that the D_{eff} values of tomato changed from 2.26×10^{-9} to 4.45×10^{-9} m²/s, and for solar tunnel and open sun drying Sacilik *et al.* (2006) found that the D_{eff} values of organic tomato were 1.31×10^{-9} and 1.07×10^{-9} m²/s. Samadi and Loghmanieh (2013) reported that D_{eff} values of apple ranged between 3.499×10^{-7}-4.746×10^{-7} m²/s and 3.671×10^{-7}-5.101×10^{-7} m²/s, respectively for hot air drying and infrared drying. Correa *et al.* (2012) calculated that D_{eff} values of tomato ranged between 2.78×10^{-7}-3.80×10^{-7} m²/s for infrared drying. These values were consistent with the calculated D_{eff} values for tomato in this presented research but the D_{eff} values were higher than those obtained for solar, open sun and hot air drying.

Quality characteristics of dried tomato slices

The vitamin C content of the dried tomato slices from all treatments was lower, while the lycopene content was higher when compared to the fresh ones. Approximately 3-52% vitamin C loss and 207-337% lycopene increase occurred during drying. The effects of IR and v were insignificant on the vitamin C, lycopene and β-carotene content of dried tomatoes (P>0.05). However, the interactions of IR×v had remarkable effects on rehydration and total colour change (Table 3).

Table 3. Physicochemical properties of dried tomato at different conditions.[1]

IR (W/m²)	*v* (m/s)	Vitamin C (mg/kg DM)	Lycopene (mg/kg DM)	β-carotene (mg/kg DM)	R_e	*ΔE*
1,830	1	2,285±64	209.1±68.6	76.3±16.5	2.76±0.14[ab]	9.29±3.27[ab]
	1.5	2,241±71	229.2±7.70	77.7±12.2	2.45±0.13[b]	10.83±4.38[ab]
	2	2,120±166	261.0±27.6	60.5±8.7	2.62±0.13[ab]	7.92±1.07[b]
2,640	1	1,921±87	298.0±58.6	60.5±6.9	2.94±0.15[a]	9.42±4.35[ab]
	1.5	2,049±134	211.4±37.3	57.6±16.3	1.97±0.10[c]	8.13±2.75[b]
	2	2,080±125	288.8±29.1	60.9±7.2	2.98±0.15[a]	10.87±7.24[ab]
3,165	1	1,335±353	246.2±15.7	47.1±2.0	2.97±0.15[a]	8.05±2.65[ab]
	1.5	1,358±360	243.3±50.8	62.4±10.7	2.53±0.13[b]	14.77±8.28[a]
	2	1,126±206	229.3±42.0	46.3±4.7	2.83±0.14[ab]	7.03±1.49[b]
Fresh tomato		2,372±193	68.2±28.2	65.1±27.3	-	-

[1] Means in column with different letters are significantly different by Tukey (P<0.05). Data represent means ± standard deviation. DM = dry matter; IR = infrared radiation intensity; *v* = air velocity; R_e = rehydration ratio; ΔE = colour change.

Kerkhofs *et al.* (2005), Toor and Savage (2006) and Khazaei *et al.* (2008) reported that increasing drying temperature resulted in lower vitamin C content in dried tomatoes. Due to the integral drying temperature and time, increasing temperature results in shorter drying time and thus reduces vitamin C loss. It was also reported that the vitamin C content of tomatoes that have been dried with convective hot air was approximately 50% lower than of fresh ones (Ashebir *et al.*, 2009). Kulanthaisami *et al.* (2010) indicated that 75.15 and 86.95% vitamin C loss occurred in tomatoes that were dried in a cabinet solar dryer and with sun drying, respectively. In this research, increasing infrared radiation intensity caused a higher heat load on the tomato slices, therefore, vitamin C content loss increased.

In the present study, we found that the lycopene content of the infrared dried tomatoes was approximately 29-364% higher than of fresh ones. This result may be attributed to the increase in the extractability or accessibility of lycopene. Dewanto *et al.* (2002) suggested that thermal processes might break down cell walls and weaken the bonding forces between lycopene and the tissue, thus enhancing the release of lycopene from the matrix.

Comparison of infrared drying conditions

Cluster analysis was carried out to determine the relationship between the different drying conditions on the basis of their operational features (drying time and E_s) (Figure 6A), the physical features of the dried tomato slices (D_{eff}, R_e and ΔE) (Figure 6B), the chemical features of the dried tomato slices (vitamin C, lycopene and β-carotene content) (Figure 6C) and all features (Figure 6D). The cluster analysis was based on the dendrograms to assess the similarity between the drying methods.

From the dendrograms, it can be seen that the drying condition at 1,830 W/m² of IR and 2.0 m/s (7) of *v* for operational features was clearly distinct from the other drying conditions belonging to the same cluster group. This same cluster group had similarity values changing between 65 and 98%. Regarding the physical features, similarity values ranged between 40 and 85, and drying conditions of 1,830 W/m²-1.0 m/s, 2,640 W/m²-1.0 m/s, 2,640 W/m²-2.0 m/s, 3,165 W/m²-1.0 m/s and 3,165 W/m²-2.0 m/s (1, 2, 8, 3 and 9) were the closest. Similarity values ranged between 53 and 84% for the chemical features of the dried tomato slices. When all of the features were evaluated together, the similarity values of drying conditions varied between 38 and 75%. Drying conditions of 1,830 W/m²-1.0 m/s and 1,830 W/m²-1.5 m/s (1 and 4), and 2,640 W/m²-1.0 m/s and 2,640 W/m²-2.0 m/s (2 and 8), and 3,165 W/m-e²-1.0 m/s and 3,165 W/m²-2.0 m/s (3 and 9) were the closest to each other, and different from the other conditions.

4. Conclusions

In this study, the effects of three infrared radiation intensities and air velocities on the drying of tomato slices in an infrared dryer were investigated. Five different thin layer models were evaluated to explain the infrared drying kinetics of tomato slices. The drying time varied between 141 and 246 min for all the drying conditions and decreased with decreasing air velocity, while it decreased with increasing infrared radiation intensity. The logarithmic model was found to give the highest R^2 and the lowest χ^2 and E_{RMS} values for all drying conditions. The logarithmic model could be used to describe the thin layer infrared drying of tomato slices. The effective moisture diffusivity increased with increasing infrared radiation intensity, while it decreased with increasing air velocity. Total colour change varied between 7.03 and 10.83. The rehydration

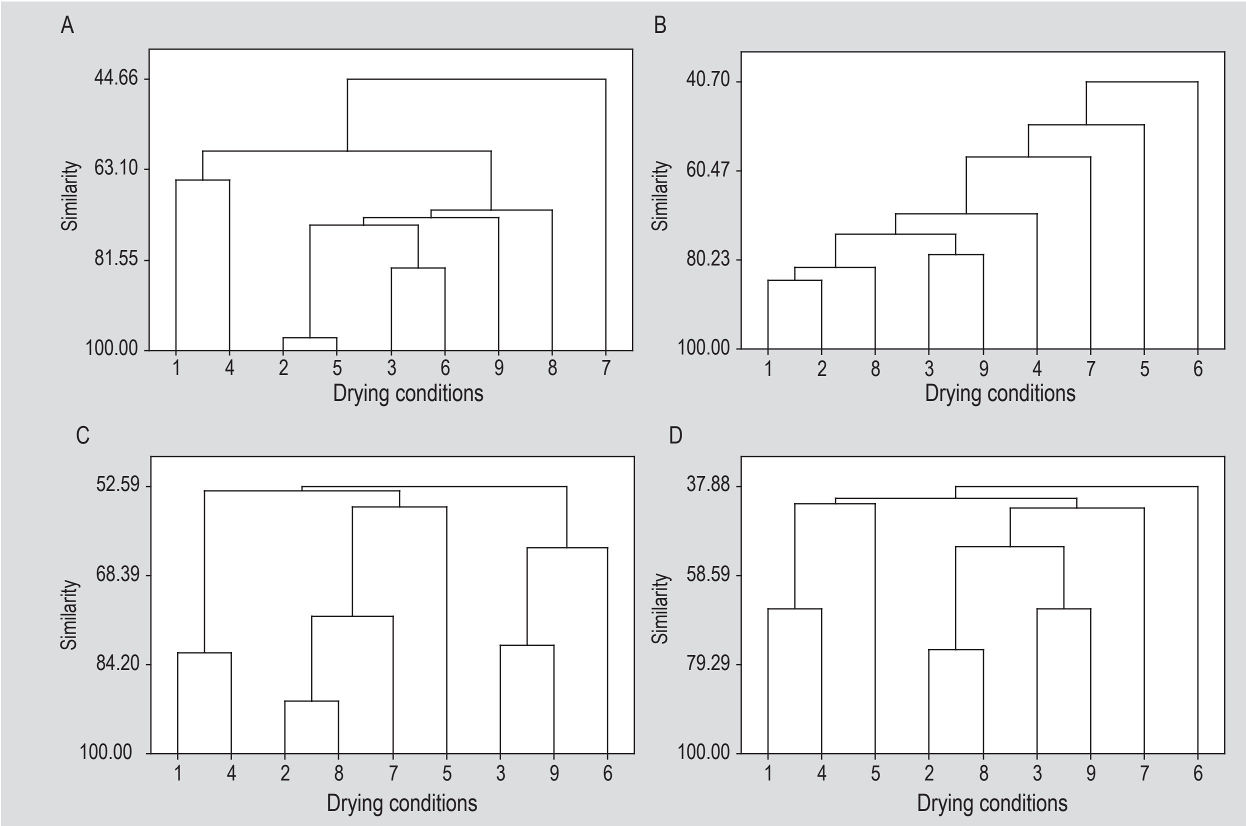

Figure 6. Two-dimensional dendrogram in the cluster analysis of the different drying conditions based on (A) operational features, (B) physical features of dried tomato slices, (C) chemical features of dried tomato slices and (D) all features.

ratio was significantly influenced by radiation intensity and air velocity. Vitamin C loss increased with increasing infrared radiation intensity. 207-337% lycopene increase occurred during drying. On the basis of operation features, and the physical and nutritional features of dried tomato, some drying conditions were highly similar.

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