BIOSCIENCE JOURNAL

THIN-LAYER DRYING CHARACTERISTICS, MODELING AND QUALITY ATTRIBUTES OF TOMATO SLICES DRIED WITH INFRARED RADIATION HEATING

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How to cite: EL-MESERY, H.S., et al. Thin-layer drying characteristics, modeling and quality attributes of tomato slices dried with infrared radiation heating. *Bioscience Journal*. 2022, **38**, e38049. https://doi.org/10.14393/BJ-v38n0a2022-42303

Abstract
An Infrared dryer was used to examine the drying of tomato slices. In this investigation, the influence of infrared radiation (IR) on the rate of drying, physical quality, energy combustion of tomato was estimated at three different levels of intensity at 0.15, 0.20, and 0.35 W/cm² under different air flows of 0.5, 1, and 1.5 m/s. Tomato slices were dried with an initial moisture content of 19.7 to 0.17 g water/g dry solids by infrared drying. The moisture content and drying rates are found to be dramatically affected by infrared density. An increase in the drying rate and a decrease in the drying period occurred with increasing infrared intensity. A decrease in energy consumption was detected with the increase of radiation intensity. The results clarified that the shrinkage ratio increased with increasing infrared intensity. The rehydration ratio raised with the increase in radiation intensity. The change in the colour difference of dried slices increased with an increase in radiation intensity. The models were in comparison using (R^2) coefficient of determination, modelling efficiency (EF), and (χ^2) reduced chi-square. Midilli model was fit for simulation of all drying conditions and could be used to estimate tomato moisture content at any time during the infrared drying process.

Keywords: Energy. Infrared drying. Modelling. Quality. Tomato.

1. Introduction

The drying process increases the shelf life of the fruits of the plants. Dehydration of the micro-organisms is suitable for the preservation of the opinion is founded, of enzymes, a metabolic system of the whole of the matter requires that the water of the biological their activities production (Sivakumar et al. 2016). The reduction of water decreases the movement and action of the water within the product, as well as the development of micro-organisms (Pochont et al. 2020). Water is the main objective of reducing moisture content of action (Corrêa et al. 2010). This product rate and respiration parameters that control the incidence of micro-organisms and insects (Goneli et al. 2010).

Dehydrating is the highest energy-concentrated (20-30%) of the energy consumption drying method of agricultural and food-processing production (Osae et al. 2020). Kocabiyik and Tezer (2009) reported that the most energy-intensive food processing industry in the drying process. The dryers are designed to reduce the energy cost in the drying. Infrared drying as a substitute drying technique for food has many advantages. These may involve less drying period, high energy efficiency, and temperature materials in standard finished products with high quality (Nalawade et al. 2019). Numerous food products productively dried by using infrared drying such as carrots (Kocabiyik and Tezer 2009), onions (El-mesery and Mwithiga 2014) seedless grapes (Celma et al. 2009) apples (EL-Mesery et al. 2021) mint leaves (Ye et al. 2021) and blueberries (Shi et al. 2008).

In order that knowledge is acquired in the study of the transition can be made to the successful experience in the industrial applications in the drying food. Also, modeling is a key tool applied to predict the overall performance of a drying method (Pochont et al. 2020). Different mathematical models, empirical and semi-empirical suggested the evaluating of food drying (Mirzaee et al. 2010). The thin layer models allow the prediction of mass transfer during drying and are used to simulate drying curves under similar conditions (Puente-Díaz et al. 2013). The paper aimed to (1) explain the impact of infrared drying conditions on drying kinetics of tomato; (2) select optimum drying models for infrared drying; (3) estimate the energy consumption and (4) determine the physical quality of tomato under infrared drying conditions.

2. Material and Methods

Materials

The fresh tomatoes were purchased from the local market. Samples were cut into slices approximately 4±1 mm thick with a sharp stainless-steel knife. Three measurements were proceeded on each slice to ensure proper thickness with callipers and their average values had been considered. To determine the initial moisture content of the tomato, about 20 g of tomato was dried in an oven at 105 °C for 24 h (AOAC 2000). Tomato slices were established to be 19.7 g water/g dry matter of initial moisture content.

Drying apparatus and procedure

The dryer was established for drying different food produces applying infrared radiation (IR) (Figure 1). A drying chamber of 50 × 40 × 50 cm was prepared from a stainless-steel sheet of 2 mm thickness. The inside sides of the drying chamber were enclosed with aluminum foil. The dryer was prepared with two tube-type infrared heaters in a drying chamber. The intensity of infrared of the radiators might be various with controlling the voltage by a power regulator. the airflow was modified by moving the fan revolution utilizing an airflow control valve. The tests were carried out at three of radiation intensity (0.15, 0.20 or 0.35 W/cm²) at airflow (0.5, 1.0 and 1.5 m/s).

Tomato slices were inserted into the dryer after about 30 minutes to achieve to conditions before each drying test. 500 g of slices were located as thin layers in the drying chamber. Tomato mass was evaluated by a digital electronic balance with an accuracy of ± 0.01g with every 10 min during drying. The dehydrating of samples continued until moisture content in the slides decreased to approximately ± 0.07 grams of water / dry matter.

Mathematical modelling of the drying kinetics

The data of drying tomato was fitted with eleven models given in Table 1. Moisture ratio through drying is established utilizing Eq. (1).

$$MR=\frac{M-M_e}{M_i-M_e} \qquad (1)$$

M = Moisture content of the sample at any time,
Me = Equilibrium moisture content of sample,
Mi = Initial moisture content in samples in kg water/kg dry matter,
k = Drying constant (in units of 1/min) and
t = Drying period in min.

For all conditions under study, the rate of (M-Me)/(Mi-Me), a moisture content was found by (EL-Mesery and Mao 2017; Jahanbakhshi et al. 2020) (Eq.2):

$$MR = \frac{M}{M_i} \qquad (2)$$

Table 1. Mathematical models used to predict drying behavior.

Name of model	Model equation	References
Newton	$MR = \exp(-kt)$	(Ayensu 1997)
Henderson and Pabis	$MR = a.\exp(-kt)$	(Henderson and Pabis 1961)
Page	$MR = \exp(-kt^n)$	(Page 1949)
Modified Page	$MR = \exp[-(kt)^n]$	(Özdemir and Devres 1999)
logarithmic model	$MR = a\exp(-kt) + c$	(Yagcioglu 1999)
Two-term	$MR = a\exp(-k_0t) + b\exp(-k_1t)$	(Madamba et al. 1996)
Wang and Singh	$MR = 1 + at + bt^2$	(Wang and Singh 1978)
Modified Henderson and pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	(Karathanos 1999)
Midilliet al.	$MR = a\exp(-kt^n) + bt$	(Midilli et al. 2002)
Thomson	$t = a\ln(MR) + b[\ln(MR)]^2$	(Thompson et al. 1968)
Verma et al.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	(Verma et al. 1985)

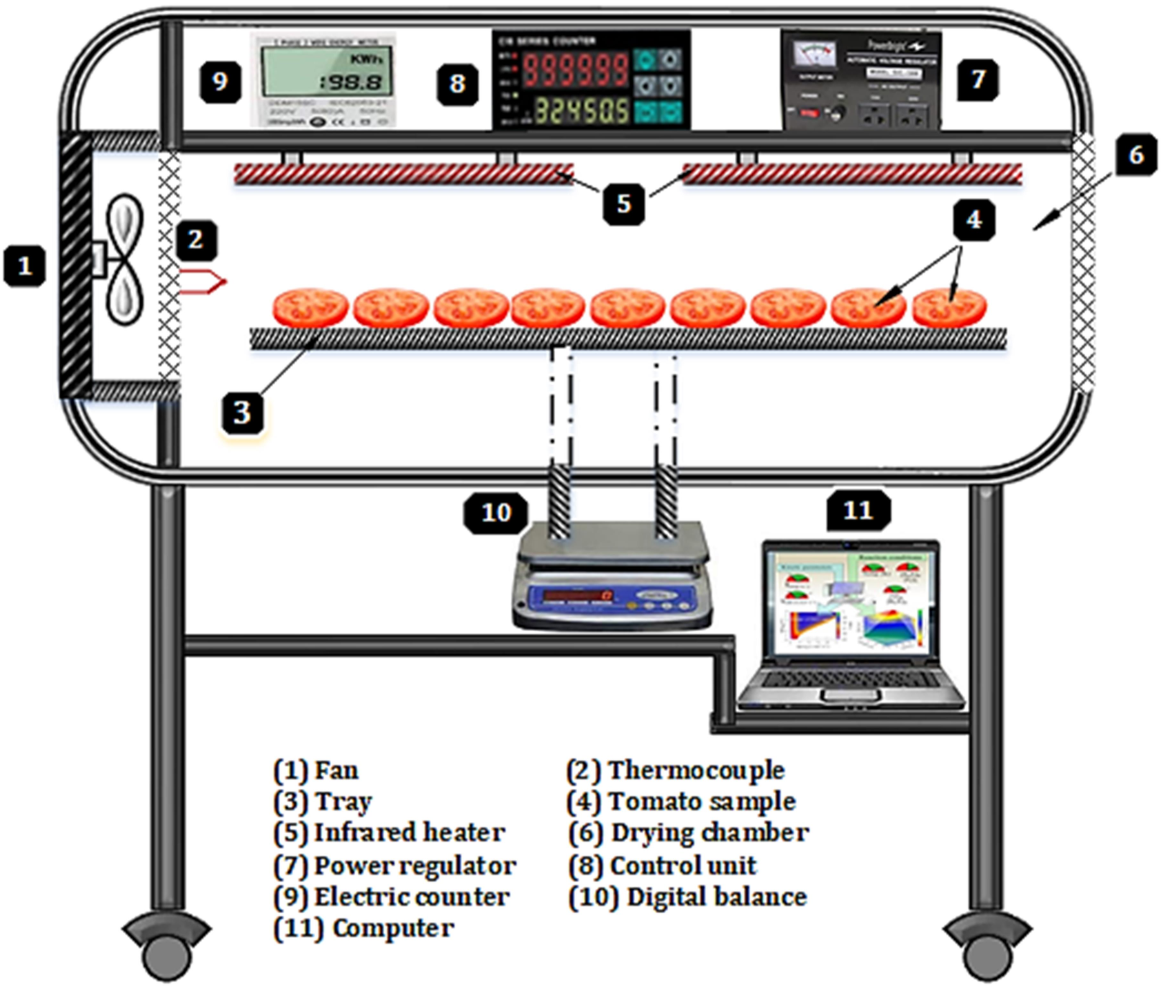

Figure 1. Schematic diagram showing the infrared dryer.

Statistical analysis

The goodness of mathematical models on the data assessed by determination coefficient (R^2) [Eq. (3)]; modelling efficiency (EF), [Eq. (4)] and chi-square test (χ^2) [Eq. (5)] with higher (R^2 and EF) rates and lower χ^2 rates showing an improve fit (Kouhila et al. 2020; Moussaoui et al. 2021).

$$R^2=\frac{\sum_{i=1}^{N}\left(MR_{exp.i}\text{-}MR_{Pre.i}\right)^2}{\sqrt{\left[\sum_{i=1}^{N}\left(MR_{exp.i}\text{-}MR_{Pre.i}\right)^2\right]*\left[\sum_{i=1}^{N}\left(MR_{exp.i}\text{-}MR_{Pre.i}\right)^2\right]}} \qquad (3)$$

$$EF=\frac{\sum_{i=1}^{N}\left(MR_{exp.i}\text{-}MR_{exp\ mean.i}\right)^2-\sum_{i=1}^{N}\left(MR_{exp.i}\text{-}MR_{Pre.i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp.i}\text{-}MR_{exp\ mean.i}\right)^2} \qquad (4)$$

$$\chi^2=\frac{\sum_{i=1}^{N}\left(MR_{exp.i}\text{-}MR_{pre.i}\right)^2}{N\text{-}n} \qquad (5)$$

$MR_{exp\ .i}$ = the i^{th} experimental moisture ratio,
$MR_{pre.i}$ = the i^{th} predicted moisture ratio,
N and n are the number of observations constants, respectively.

Rehydration ratio (Rr)

The of dried sample of tomato (10 g) in 50 ml of water at 35 ^{o}C temperature for 5 h to determine the rehydration ratio (EL-Mesery and Mwithiga 2012). The rehydration ratio was calculated as follow using Eq.6:

$$Rr=\frac{\text{mass after rehydration}}{\text{mass before rehydration}} \qquad (6)$$

Shrinkage ratio (Sr)

The ratio of shrinkage for dried tomato was estimated by using a volumetric displacement technique by n-heptane (Velić et al. 2007). slices (10) were checked, and the average values were described. The Equation 7 evaluated shrinkage ratio (Sr) of tomato slices.

$$S_r=1\text{-}\frac{V_d}{V_o} \qquad (7)$$

where V_o and V_d is the average volume of slices before and after drying, respectively.

Colour parameters (δE)

The Hunter Lab Colour colorimeter has been used for measured tomato colour The change of colour (δE) of dried samples was described in Eq. 8 (Zeng et al. 2019).

$$\delta E=\sqrt{\left(L_o\text{-}L\ \ \right)^2+\left(a_o\text{-}a\ \ \right)^2+\left(b_o\text{-}b\ \ \right)^2} \qquad (8)$$

where L, a, b were the brightness, redness, and yellowness of the dried slices, respectively.

Energy consumption

The energy consumption was characterized as the totality of electrical energy used through drying. The total energy consumption is the totality of energy used by the infrared lamp and the fan. A digital electric counter with an accuracy 0.01 kWh was used for measuring the total energy on the system.

3. Results and Discussion

Drying kinetics

The influence of the IR intensity on the moisture ratio of tomato slices is presented in Figure 2A. The drying time required to dry tomato slices from a moisture content of 95 ± 1 % (w.b.) to 10 ± 1% (w.b.) was 360, 315, and 252 min at IR intensities of 0.15, 0.20, and 0.35 W/cm², respectively. It is seen that the drying period decreases with the increasing intensity of radiation. The results showed that mass removal within the slices was faster with higher infrared intraday radiation since more heat was created within the matters creation a higher vapor pressure difference between the middle and the outside of the slices. Similar results were informed by (Doymaz 2014; Onwude et al. 2019).

The effect of drying settings on the drying period of tomato slices by the infrared dryer is revealed in Figure 2B. With a decrease in the air velocity and an increase in the IR of the infrared heaters, the drying time increased. This may be credited to the cooling of the slice's surface by increasing air velocity using the infrared dryer. Similar results were recorded (Motevali et al. 2014). The relationship was created between drying time, radiation intensity (IR) and air velocity (V) and showed in Eq.9.

$$\text{Drying time}=\frac{420\text{-}7.8V\text{-}2369IR+4019IR^2}{1\text{-}0.13V\text{-}4.6IR+8.3IR^2} \qquad R^2=0.99 \qquad (9)$$

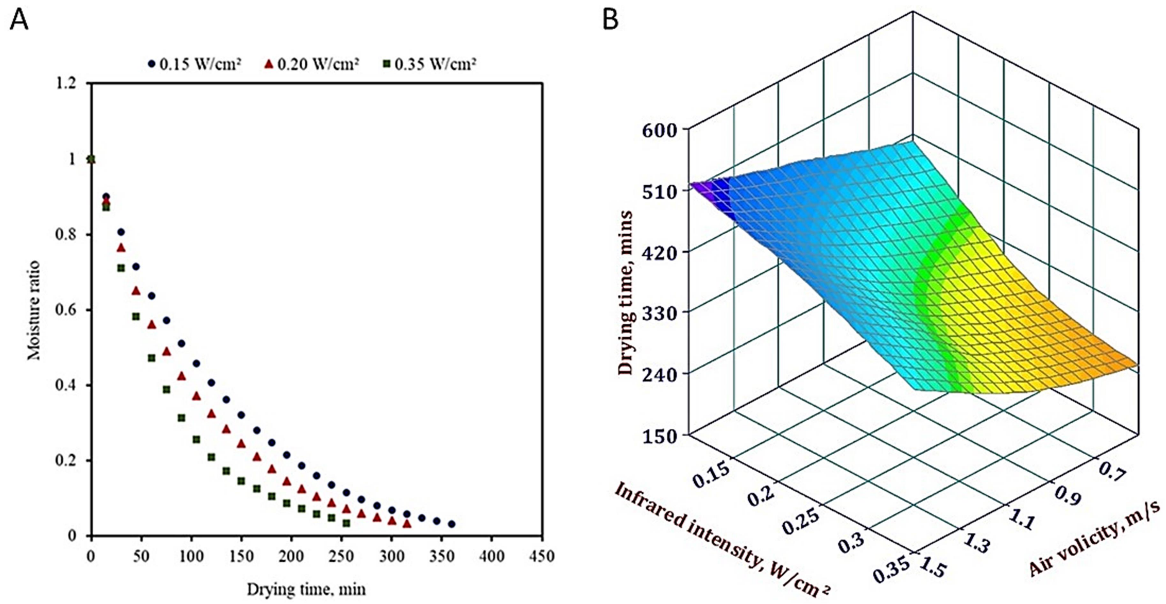

Figure 2. A - Effect of interaction between air velocity and radiation intensity on moisture content and B - drying time of tomato slices.

Mathematical modeling drying data

The results of statistical are reviewed in Table 2. In all drying systems, the statistical parameter estimates presented that R², EF, and χ² values ranged from 0.985 to 0.9998, 0.988 to 0.998, and 0.0001 to 0.0005, respectively. Based on the greatest value of R2, EF, and least values of χ2 determined that the Midilli et al. model contributed the greatest results than the other models (Vega-Gálvez et al. 2014).

The Midilli et al. (2002) model was fitted to experimental data under different infrared dryer sitting (Djebli et al. 2020). Drying constants k, b, and coefficients a, n of the model and with the statistical variables of the goodness of fit are presented in Table 3.

Shrinkage ratio

Figure 4A indicates the shrinkage ratio of slices dried at different drying conditions using the infrared dryer. The ratio of shrinkage for dried slices under various intensities is presented in Figure 4B. Increasing the radiation intensity from 0.15 to 0.35 W/cm2 affected the shrinkage ratio to decrease from 0.25 to 0.14. Analysis of effects of drying air velocity and IR intensity on shrinkage ratio showed a decrease in shrinkage ratio by rising intensity. While increase with increasing the drying air velocity. The low shrinkage under the higher intensity of infrared can be approved to higher temperatures of slices and less moisture content of the outside surfaces of the slice (Maskan 2001). The relationship was founded between shrinkage ratio (Sr), radiation intensity (IR), and airflow (V) present in Eq. 11.

$$Sr= \frac{0.23-1.5IR+2.7IR^2-0.007V}{1-6.4IR+11.7IR^2-0.55V} \quad R^2=0.99 \qquad (11)$$

Table 2. Statistical results obtained from various thin layer drying models.

Name of Model	Infrared intensity, W/cm^2	R^2	χ^2	EF
Newton	0.15	0.995	0.0023	0.996
	0.20	0.998	0.0025	0.999
	0.35	0.995	0.0096	0.992
Henderson and Pabis	0.15	0.997	0.0036	0.998
	0.20	0.998	0.0009	0.997
	0.35	0.998	0.0012	0.999
Page	0.15	0.998	0.0009	0.998
	0.20	0.999	0.0025	0.999
	0.35	0.999	0.0006	0.998
Modified Page	0.15	0.997	0.0008	0.998
	0.20	0.996	0.0009	0.995
	0.35	0.998	0.0007	0.997
Logarithmic	0.15	0.998	0.0063	0.997
	0.20	0.997	0.0085	0.998
	0.35	0.996	0.0012	0.995
Two-term	0.15	0.991	0.0055	0.992
	0.20	0.995	0.0036	0.996
	0.35	0.997	0.0096	0.998
Modified Hend. & Pabis	0.15	0.997	0.0052	0.997
	0.20	0.995	0.0069	0.995
	0.35	0.982	0.0009	0.981
Midilli et al	0.15	0.999	0.0005	0.999
	0.20	0.999	0.0004	0.999
	0.35	0.999	0.0003	0.999
Verma et al	0.15	0.992	0.0025	0.991
	0.20	0.998	0.0069	0.997
	0.35	0.998	0.0091	0.997
Wang and Sing	0.15	0.998	0.0098	0.995
	0.20	0.998	0.0088	0.996
	0.35	0.987	0.0063	0.988
Thompson	0.15	0.999	0.0077	0.995
	0.20	0.997	0.0008	0.998
	0.35	0.994	0.0009	0.998

Table 3. Results of statistical analysis on Midilli et al. model at different IR intensities and air velocities.

Infrared Intensity, W/cm^2	Air Velocity, m/s	k	a	n	b	R^2	EF	χ^2
0.15	0.5	0.0090	1.03	1.081	0.00007	0.9998	0.9997	0.00051
	1.0	0.0071	1.02	1.062	0.00049	0.9998	0.9999	0.00031
	1.5	0.0065	1.01	1.051	0.00082	0.9998	0.9998	0.00015
0.20	0.5	0.0097	1.20	1.061	0.00009	0.9997	0.9997	0.00041
	1.0	0.0062	1.18	1.042	0.00007	0.9999	0.9999	0.00037
	1.5	0.0057	1.09	1.051	0.00065	0.9998	0.9985	0.00015
0.35	0.5	0.0122	1.29	1.037	0.0047	0.9998	0.9996	0.00032
	1.0	0.0110	1.15	1.076	0.00021	0.9999	0.9989	0.00024
	1.5	0.0109	1.29	0.945	0.00048	0.9998	0.9998	0.00015

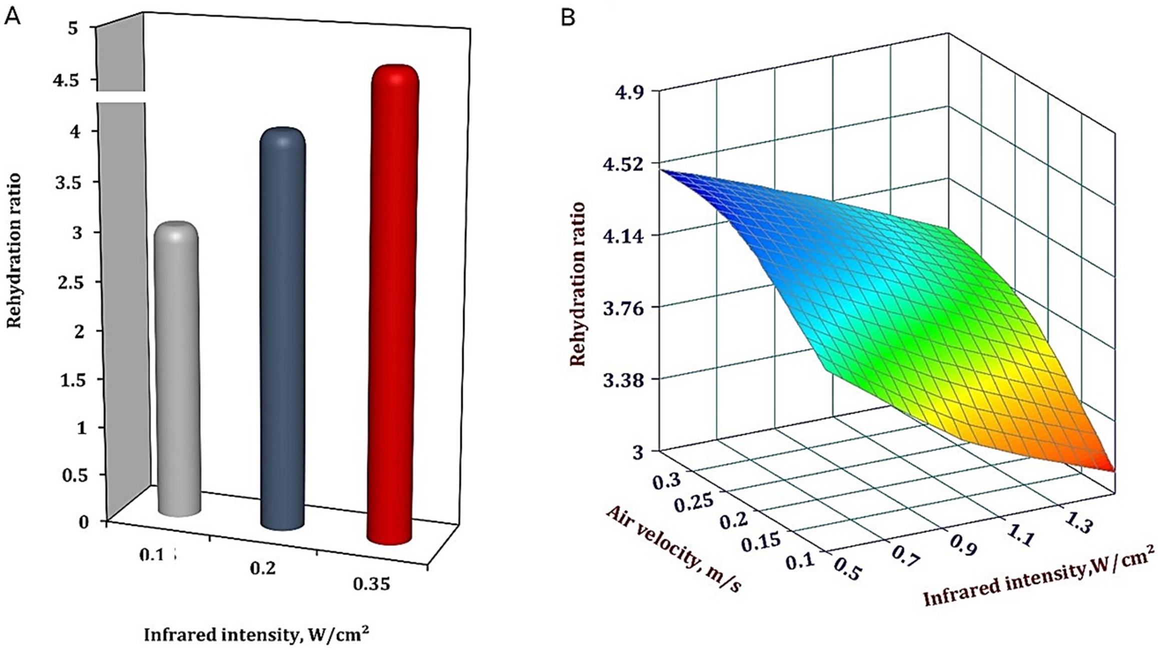

Figure 3. A - Effect of interaction between radiation intensity and B - air velocity on the rehydration rate of dried tomato slices.

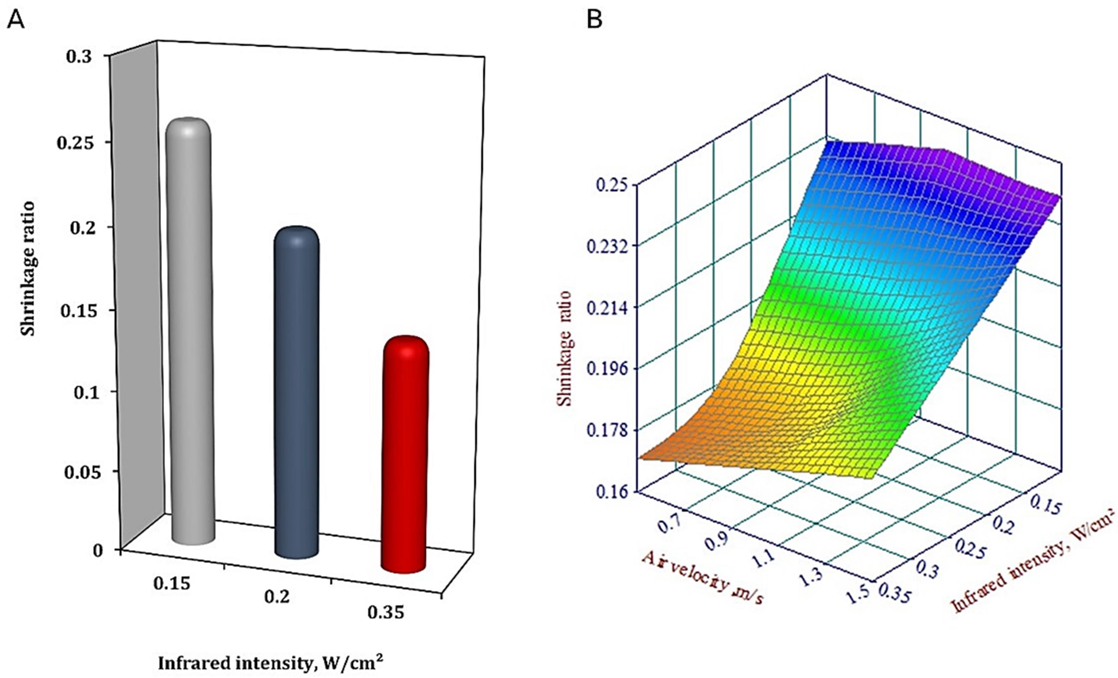

Figure 4. A - The effect of the interaction between radiation intensity and B - air velocity on the shrinkage of dried tomatoes.

Colour parameters

The colour difference of dried tomato slices at several drying infrared intensities is given in Figure 5A. The total change in colour increased with increasing in IR intensity (Puente-Díaz et al. 2013). The relationship between total colour difference (δE), radiation intensity (IR), and airflow (V) was proved and showed in Figure 5B and Eq. 12. and Eq. 12. The change of colour for dried tomato slices increased with increasing IR intensity while it decreased with increasing air velocity (Puente-Díaz et al. 2013).

$$\partial E=\frac{5.2\text{-}28.2IR+49IR^2\text{-}0.7V}{1\text{-}6.7IR+11.8IR^2\text{-}0.04V} \quad R^2=0.99 \quad (12)$$

Energy consumption

Result of influence intensity of radiation on the consumption of energy is given in Figure 7(A, B). At constant of air flow (0.5 m/s) the lowest consumption of energy is 0.7 kW.h and was found at intensity 0.35 W/cm^2. While the highest consumption was 1.8 kW.h with 0.15 W/cm^2. A decrease in energy consumption was detected with increase of radiation intensity. The rise in intensity reasons an increase in the temperature of the slices then the rate of evaporation. Higher intensities increase the temperature of the slices and thus the rate of evaporation. The increasing of rate evaporation causes a decrease in the drying period and energy consumption (EL-Mesery et al. 2019). The relationship was created between specific energy consumption, and different drying conditions by using infrared dryer and presented in Eq.13.

$$Energy=\left(3.6\text{-}20.4IR+31.4IR^2\text{-}0.02V\right)/\left(1\text{-}1.5IR\text{-}0.23V\right) \quad R^2=0.99 \quad (13)$$

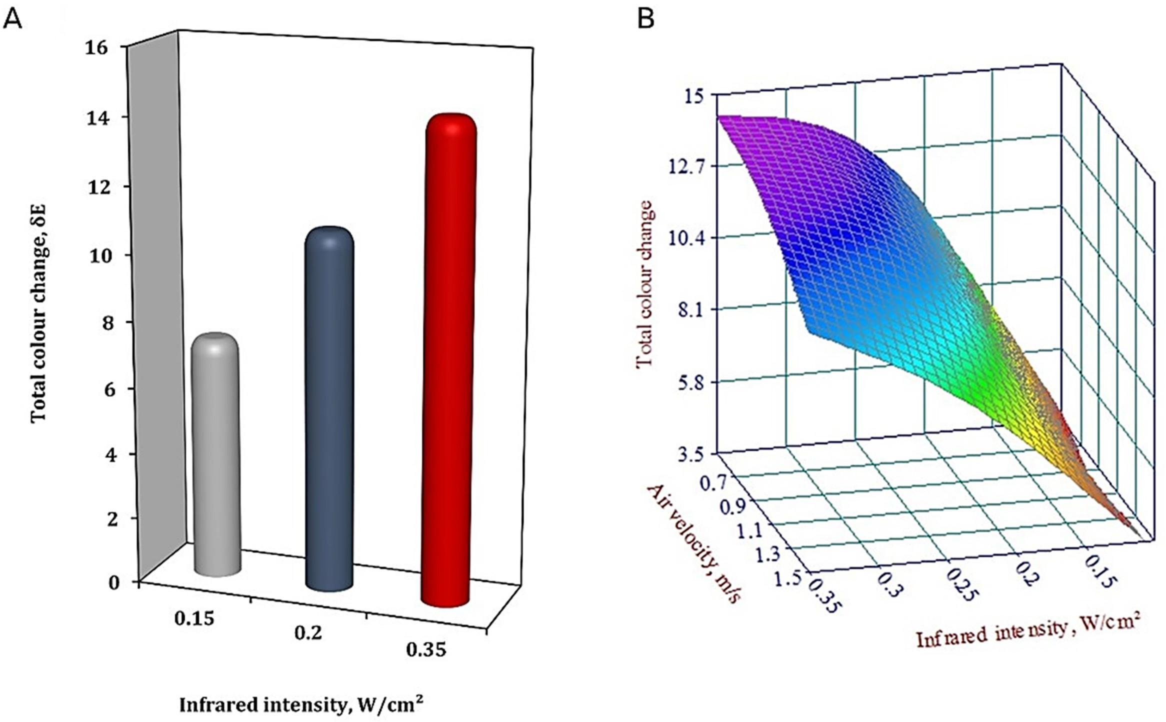

Figure 5. Interaction effect of infrared drying intensity on colour difference changes of dried tomato slices.

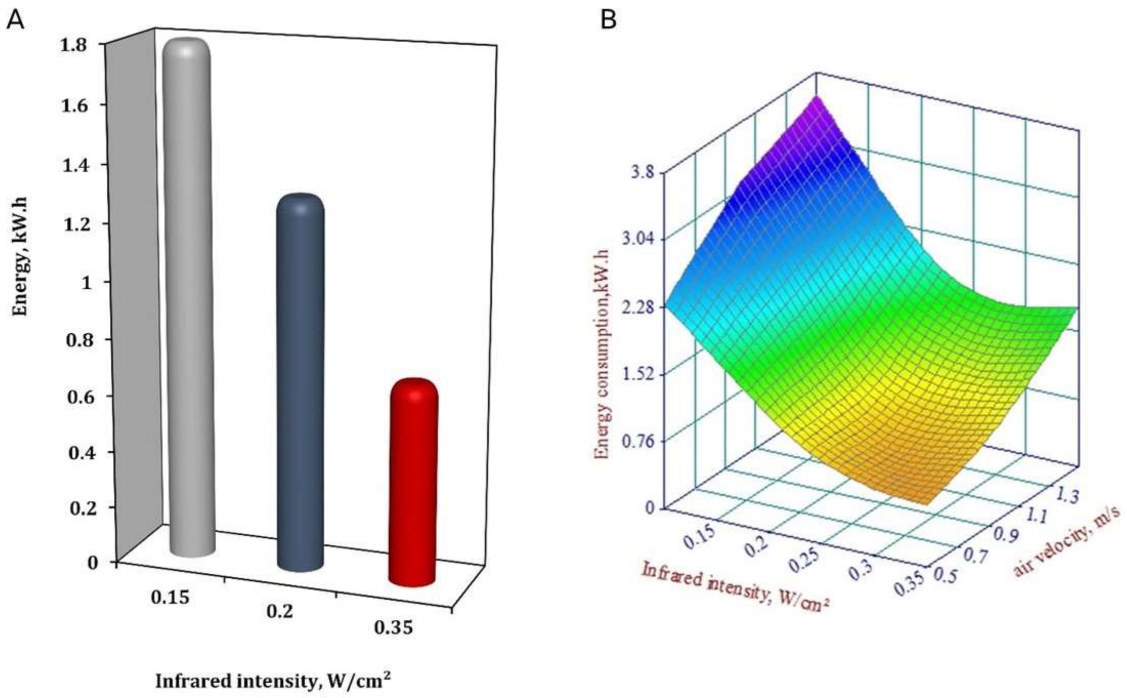

Figure 6. Variation of energy consumptions from the effect of infrared intensity and air velocity on tomato drying.

4. Conclusions

The influence of various IR intensities on the drying of tomato slices was studied. According to the results, the drying period was performed to reduce with increasing infrared intensity. The Midilli model provided the greatest image of drying statistics with all drying settings. The rehydration ratio was set to increase with an increase in infrared intensity. A decrease in energy consumption was detected with the increase of radiation intensity.

Authors' Contributions: EL-MESERY, H.S.: Conception and design, methodology acquisition of data, analysis and interpretation of data, drafting the manuscript, visualization, supervision, funding acquisition, approved the final version of the manuscript, KAMEL, R.M.: Acquisition of data, analysis and interpretation of data, ALSHAER W.G: Conception and design, visualization, funding acquisition, approved the final version of the manuscript, All authors have read an approved the final version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Ethics Approval: Not applicable.

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Received: 15 May 2020 | **Accepted:** 30 August 2021 | **Published:** 12 August 2022