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# Mathematical Modelling of Thin Layer Drying Kinetics of Onion Slices Hot-air Convection, Infrared Radiation and Combined Infrared-Convection Drying

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**ABSTRACT**

Onion slices were dried in convection hot-air, infrared radiation and combined infrared-convection hot air dryers. A systematic experimental design was applied to analyse drying kinetics due to the effect of type of dryer, infrared radiation intensity, drying air temperature and drying air velocity, until a final moisture content of 7 ± 1 % (wet basis) was attained. Mathematical modelling of thin layer drying kinetics under the different drying methods were studied and verified with experimental data. Eleven different mathematical drying models were compared according to three statistical parameters namely, the correlation coefficient ($R^2$), chi-square ($\chi^2$) and modelling efficiency (EF). Drying curves obtained from the experimental data were fitted to the-thin layer drying models. The results show that, the Midilli et al. model obtained the highest (EF and $R^2$) value and the lowest ($\chi^2$) values for both dryers. Therefore, this model is the best for describing the drying curves of onion slices under all the drying processing conditions.

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## INTRODUCTION

Fruits and vegetables play a very important role in our diet and nutrition, since they are a source of not only raw fibre but also essential nutrients, vitamins and minerals. The seasonal nature of the production of many fruits and vegetables, together with their high water content which makes them perishable, has led to the search for different preservation technologies (refrigeration, drying processes, etc.) to preserve them and to permit us to make these products available at any time [1]. One of the simplest methods to improve the shelf life of fruits and vegetables is to reduce their moisture content to such extent that the microorganism growth is minimal [2].

Onion (*Allium cepa L.*) is a strong-flavoured vegetable used in a wide variety of ways, and its characteristic flavour (pungency) or aroma, biological compounds and medical functions are mainly due to their high organo-sulphur compounds [3]. Dehydrated onion has become a standard food ingredient in a wide range of food products such as ketchup, soups, salad dressings, sausage and meat products, potato chips, crackers, and many other convenience foods [4].

Drying is the most energy intensive process of the food processing industry. Open-air and hot air drying methods are frequently used for agricultural products drying. Open-air drying is preferred in rural areas whereas hot air drying is the most common technique being used in industrial applications. Hot air drying method has some disadvantages such as low thermal conductivity, long drying time and quality degradation in terms of nutritional values, colour, shrinkage and other organoleptic properties. Therefore, new techniques that increase drying rates and enhance product quality are trying to be improved [5]. Infrared technology became a practical alternative due to the versatility, simplicity of the required equipment, fast response of heating and drying, easy installation and low capital cost [6]. Moreover, combinations of infrared and hot air drying has been reported to be more efficient than irradiation or hot air drying alone, presumably providing a synergistic effect [7,8,9].

In order to successfully transfer knowledge acquired experimentally from studies on food dehydration into industrial applications, mathematical modelling 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 [10]. Numerous mathematical models, empirical and semi-empirical, have been proposed to estimate the drying characteristics of agricultural products [11]. These simple models, also known as thin layer

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models, allow prediction of mass transfer during dehydration and are applied to simulate drying curves under similar conditions [12,13].

However, few reports have focused on the evaluation of a suitable drying model for describing the drying process and influences of different temperatures and velocity and infrared radiation intensity on the drying kinetics of onion slices using different drying methods. Therefore, the aim of this study was to: (1) investigate the effect of different air temperatures and velocity and infrared radiation intensity on the drying time of onion slices using different drying methods (hot-air convection (HA); infrared drying (IR) and combined infrared radiation and hot air convection (IR-HA) drying), (2) model the thin layer drying of onion slices by fitting well-known mathematical drying models to the experimental data obtained by different drying methods under different dryer settings.

## MATERIALS AND METHODS

*Sample preparation:*

The fresh onions (*Allium cepa L.*) of white variety were procured in bulk from the local market and were then washed under running water in order to remove adhering impurities. The onions were hand peeled, cut into slices of approximate 5±1 mm thickness with a sharp stainless steel knife in the direction perpendicular to the vertical axis. Three measurements were made on each slice for ensuring proper thickness using a calliper and their average values were considered.

*Drying apparatus:*

*Convection hot-air dryer (HA):*

The experimental convective dryer (Fig. 1-A) used in this investigation consisted of a centrifugal blower to supply the air flow, an electrical resistance air heating section, the measurement sensors and a processing chamber. The air velocity above the product was measured with an anemometer (Testo 405 V1) with an accuracy of ±0.1 m/s. The air is heated by passing through the electrical resistance heaters and directed in a way such that the flow is horizontal to the samples. The air temperature in the dryer was regulated to ±1 $^{o}$C using temperature controller type T thermocouples (Testo 925) were used to measure the air temperature to an accuracy of ±1°C.

*Infrared radiation dryer (IR):*

The experimental set-up was developed for drying different agricultural products using infrared energy as shown schematically in Fig. 1. A drying chamber of 50 × 40 × 50 cm was made from stainless steel sheet of 2 mm thickness. The inner sides of the drying chamber were covered with an aluminium foil. The dryer was equipped with two tube type incandescent heaters in a drying chamber. The distance between the heaters and drying surface was maintained constant at 15 cm throughout experiments. Infrared radiation intensity or output intensity of the heaters could be varied by regulating the voltage through a power regulator. Inlet air velocity was adjusted by changing the fan revolution using an air flow control valve.

*Combination infrared and convection dryer (IR-HA):*

A schematic view of the experimental (IR-HA) dryer is shown in Fig. (1-C). The infrared-convective dryer is comprised of two components i.e, a drying chamber having a tube type infrared heater and a hot air supply unit. Provision was made in the dryer so that both the infrared radiation intensity and the air temperature could be varied by regulating the voltage through a power regulator. The air velocity was regulated with the help of a damper placed in the air supply line to the drying chamber. Moreover, this dryer has a suction centrifuge fan that air flow passed in parallel the bed product.

The dryers were run without the sample for about 30 minutes in order to reach set conditions before each drying experiment. Drying runs at each experimental setting of infrared intensity, air temperature and air flow velocity were repeated three times and the average values were recorded. After dryer preparation and adjustment for desired conditions according to the experimental plan, a 500 g mass of onion slices was placed in the drying chamber in a single layer. Every 15 minutes throughout the drying period, the mass of the drying onions was measured using a digital electronic balance (METTLER PM30, Germany) having an accuracy of ± 0.01g. The drying process was continued until the moisture content of onion slices was reduced to approximately 0.07 g water/g dry matter.

*Convection hot-air drying procedure:*

The drying air temperature for onion slices varied in the range of 50, 60 or 70 $^{o}$C. The dryer was operated at the air velocity levels of 0.5, 1 or 2 m/s.

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*Infrared radiation drying procedure:*

The dryer was set at infrared radiation intensities of 0.15, 0.20 or 0.30 W/cm$^2$ and three air velocities of 0.5, 0.7 or 1.0 m/s were applied at 25 ±1$^o$C, ambient air temperature (no heating).

*Combination infrared and convection drying procedure:*

The experiments were carried out at three levels of radiation intensity 0.15, 0.20 or 0.30 W/cm$^2$ and three air temperature levels of 40, 50 or 60 $^o$C at three air velocity levels of 0.5, 0.7 or 1 m/s. Since there were three temperature settings, three air velocity settings, three infrared radiation intensity and three dryers, there were a total of 45 runs.

*Determination of Moisture Content:*

The hot air oven method [14] was used to determine the initial moisture content of the onion. A pre weighed onion sample of 20 g was kept in a pre-dried and weighed moisture box in oven at 150 ºC for 24 hours. The dried samples were cooled in desiccators to room temperature and then weighed using an electronic balance. The moisture content (d.b) of each sample which was expressed as g water/g dry matter was used for calculations. The initial moisture content of the onion sample varied between 7.30 and 5.99 g water/g dry matter

*2.7. Mathematical modelling of the drying kinetics:*

A number of theoretical, semi-theoretical and empirical drying models have been reported in the literature. The most frequently used type of model for thin layer drying is the lumped parameter type, such as the Newton equation [15, 16, 17]. Other popular models were also considered in this study and are presented in Table 1. The moisture ratio during drying is determined using Eq. (4).

$$MR = \frac{M - M_e}{M_i - M_e} \quad (4)$$

Where M is the moisture content of the product at any time, $M_e$ is the equilibrium moisture content, $M_i$ is the initial moisture content all in kg $_{water}$/kg $_{dry\ matter}$, k is the drying constant (in units of 1/min) and t is the drying time in min.

In this analysis, it was assumed that the moisture gradient driving force during drying is a liquid concentration gradient; meanwhile the effect of heat transfer was neglected as a simplifying assumption. For all experimental conditions, the value of ($M$-$M_e$)/ ($M_i$-$M_e$), a dimensionless moisture content was obtained. Because samples were not exposed to uniform relative humidity and temperature continuously during drying, the moisture ratio was simplified as recommended by Akgun and Doymaz [18], Doymaz [19] and Sharifian et al. [20] and expressed as follow:

$$MR = \frac{M}{M_i} \quad (5)$$

*2.7. Statistical Analysis:*

For mathematical modelling, the equations in Table 1 were tested to select the best model for describing the drying curve equation of the onion slices. The moisture ratio of the onion slices during drying was calculated using equation (5). The goodness of fit of the tested mathematical models on the experimental data was evaluated using coefficient of determination ($R^2$) [Eq. (6)]; modelling efficiency (EF), [Eq. (7)] and chi-square test ($\chi^2$) [Eq. (8)] with higher ($R^2$ and EF) values and lower $\chi^2$ values indicating a better fit [21].

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp.i} - MR_{Pre.i}\right)^2}{\sqrt{\left[\sum_{i=1}^{N}\left(MR_{exp.i} - MR_{Pre.i}\right)^2\right] * \left[\sum_{i=1}^{N}\left(MR_{exp.i} - MR_{Pre.i}\right)^2\right]}} \quad (6)$$

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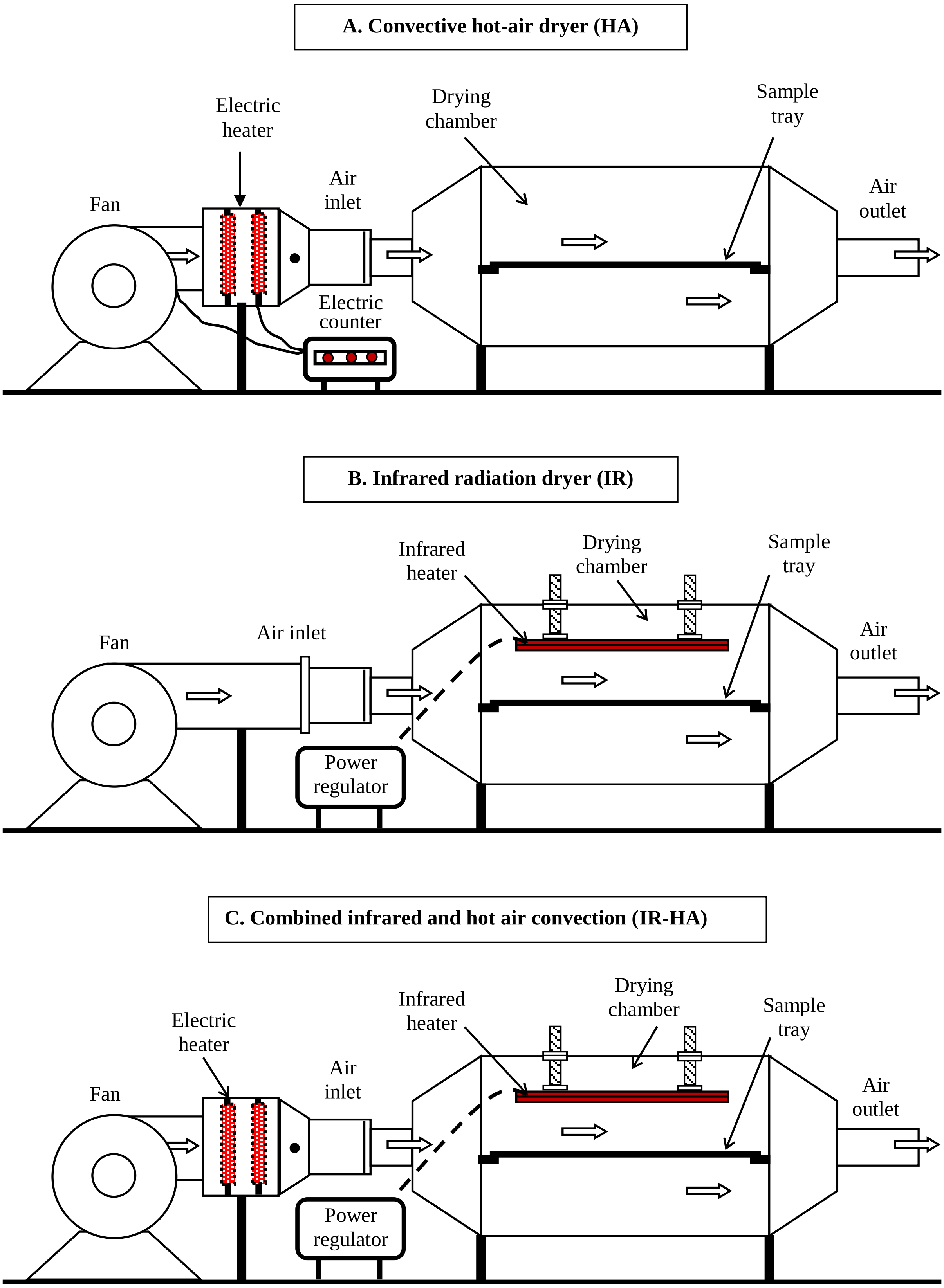


**Fig. 1:** Schematic diagram of the experimental dryers.

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$$EF = \frac{\sum_{i=1}^{N}\left(MR_{exp.i} - MR_{expmean.i}\right)^2 - \sum_{i=1}^{N}\left(MR_{exp.i} - MR_{Pre.i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp.i} - MR_{exp\,mean.i}\right)^2} \tag{7}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp.i} - MR_{pre.i}\right)^2}{N - n} \tag{8}$$

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

**Table 1:** Mathematical models applied to the drying curves.

| Name of model | Model equation | References |
|---|---|---|
| Newton | MR = exp (-kt) | [22] |
| Henderson and Pabis | MR = a.exp(-kt) | [23] |
| Page | MR = exp ($-kt^n$) | [24] |
| Modified Page | MR = exp [$-(kt)^n$] | [25] |
| logarithmic model | MR=aexp(-kt)+ c | [26] |
| Two-term | MR= a exp($-k_0t$)+ b exp($-k_1t$) | [27] |
| Wang and Singh | MR = 1 + at + $bt^2$ | [28] |
| Modified Henderson and pabis | MR = a exp(-kt) + bexp(-gt) + c exp(-ht) | [29] |
| Midilliet al. | MR = aexp($-kt^n$) + bt | [30] |
| Thomson | t = a ln(MR) + b$[\ln(MR)]^2$ | [31] |
| Verma et al. | MR = a exp(-kt)+(1-a)exp(-gt) | [32] |

## RESULTS AND DISCUSSION

*Influence of different drying methods on drying kinetics under varied processing conditions:*

The drying kinetic of the drying product varied with the type of dryer, drying air temperature, air velocity and infrared intensity are discuss in subsequent subsections below.

*Convective hot-air drying (HA):*

The variation of moisture ratio with drying time at hot air temperatures of 50, 60 and 70 $^{o}$C for onion sliced of 5 mm thickness and at 0.5, 1.0 and 2 m/s drying air velocities are shown in Fig. 2. The moisture ratio of onion slices decreased exponentially with the drying time, which is typical for food products [33]. It can be seen that the drying air temperature had a significant influence on the moisture content of the onion slices. In other words, the increase in drying air temperature and air velocity resulted in a decrease in drying time. As result, the drying curve became steeper inducing higher moisture removal.

Mota et al., [34] have recently studied drying kinetics and nutritional evaluation for convection hot air drying of onion at three different temperatures ranging from 30 to 70 $^{o}$C. They estimated the effect of drying temperature on drying kinetics and the chemical composition of onion. Their research revealed that air temperature has an important role during hot-air drying, also as it contributes to a more homogeneous and faster drying process.

To reach safe final moisture content, the drying time was 525 min at a drying air temperature of 70 $^{o}$C and increased to 675min at 50 $^{o}$C if the drying air velocity was held constant at 0.5 m/s. The corresponding values were 390 and 600 min at a drying air velocity of 1.0 m/s and 330 and 480 min at velocity of 2.0 m/s, respectively (Fig.3). A regression analysis on drying time with the process variables resulted in Eq. 9.

$$Drying\ time = \frac{(883.05 - 6.04\,T - 502.73\,V + 183.55\,V^2)}{(1 - 0.0037\,T - 0.67\,V + 0.29\,V^2)} \quad R^2 = 0.997 \tag{9}$$

where, $T$ is drying air temperature ($^{o}$C) and $V$ is air velocity (m/s).

*Infrared radiation drying (IR):*

The moisture ratio versus drying time curves for infrared radiation drying of onion slices at 25 $^{o}$C air temperature in drying chamber as influenced by the infrared intensities and air velocities are shown in Fig.4. The intensity of IR radiation had a significant effect on the moisture ratio of the onion slices as expected. The results showed that drying time decreased when the infrared power level increased. Motevali et al., [35] and Ponkham et al. [36] also observed increased drying rates and decreased drying time of food products with increasing intensity of infrared radiation. The increase in infrared power might have caused a rapid increase in the temperature at the surface of product, resulting in an increase in the water vapour pressure inside the product and thus in higher drying rates [37]. The air velocity also influenced the drying time of the onion slices (Fig.4).

At a given infrared intensity, an increase in air velocity resulted in an increase in the drying time. This trend was observed at all infrared radiations levels within the range of this study. The increase in air velocity accelerated the cooling effect, reducing the temperature at the surface of product thus the water vapour pressure or the moisture driving force [38,39].

The drying times required to reach the final moisture content of samples at three drying velocities of 0.5 0.7 and 1.0 m/s ranged from 465 to 540 min, 420 to 495 min and 390 to 465 min at infrared radiation intensities 0.15, 0.2 and 0.3 W/cm2, respectively (Fig.5). Using multiple regression analysis, a relationship was established between drying time, intensity of infrared radiation and air velocity. The relevant equation and coefficient of determination are present in Eq. 10.

$$Drying\ time = \frac{(583.85 - 652.32\,IR - 1290.85\,V - 531.94\,V^2)}{(1 + 9.41\,IR - 18.55\,V + 0.31\,V^2)} \quad R^2 = 0.999 \tag{10}$$

Where, IR is the intensity of infrared radiation (W/cm2) and V is air velocity (m/s).

*Combined infrared and hot air convection drying (IR-HA):*

The influence of infrared intensity, air temperature and air velocity on drying characteristic curves of the onion slices during combination drying are shown in Fig.6. It is clear that the drying time decreases with increase in both radiation intensity and air temperature. This phenomenon is due to the increase in the intensity of radiation and the subsequent increased temperature of the onion slices. Thus, the temperature gradient of the product surface layer or underlying slices is increased, and as a result, the rate of moisture evaporation increases. Therefore, the required drying time decreases. Similar trends have been observed by several researchers [40,41,42]

The drying times required to reduce the moisture content of slices from the initial value to 0.07 g water/g dry matter in the final product at an air temperature of 40 $^{o}$C and velocity of 0.5 m/s were 405, 375 and 330 min at 0.15, 0.20 and 0.30 W/cm$^2$ of infrared intensity, respectively. The drying time reduced to 330 min when the air temperature was increased from 40 to 60 $^{o}$C, while keeping the infrared intensity level and air velocity constant at 0.15 W/cm$^2$ and 0.5 m/s, respectively. A similar drying trend was obtained for the onion slices at other experimental levels of drying air temperatures and velocities. An increase in the air velocity resulted in an increase in the drying time in all test conditions where the infrared intensity and air temperature were held constant, possibly due to the increased cooling effect at the surface of the product and thus lowering the surface temperature [9,43]. In general, the time required to reduce the moisture content to any given value was dependent on the drying conditions, being highest at an infrared power of 0.15 W/cm$^2$, 40 $^{o}$C and 1.0 m/s and lowest at an infrared power 0.30 W/cm$^2$, air temperature 60 $^{o}$C and air velocity of 0.5 m/s. The drying times observed for the onion slices, according to the experimental conditions selected in the present study, are presented in Fig. 7. Multiple regression analysis of drying time, as a function of air temperature (*T*), air velocity (*V*) and intensity of the infrared radiation (*IR*) was performed and presented by Eq. 11.

$$\text{Drying time} = 612.81 - 590.53\,(IR) - 4.53\,(T) + 151.74\,(V) \quad R^2 = 0.986 \tag{11}$$

*Fitting of mathematical models to the drying curves:*

The moisture content data observed at the drying experiment were converted into the moisture ratio (MR) and fitted to the 11 models listed in Table 1. The statistical results of the different models, including the drying model coefficients and the comparison criteria used to evaluate goodness of fit, namely, $R^2$, $\chi^2$ and EF, are listed in Table 2. In all cases, $R^2$ and EF values for all models under study were higher than 0.98 and 0.97, respectively and $\chi 2$ values were lower than 0.002.

For all drying methods, the Midili et al model gives the best fit of experimental values since the highest values of R2 and are EF 0.0998 and 0.999, respectively, and the lowest values of $\chi 2$ (0.0004) were obtained (Table 2). Accordingly, the Midili et al model is selected as a suitable model to represent the thin layer drying behaviour of onion slices under different drying methods and different dryer settings. The Midilli et al. model has also been suggested by others in the drying of apple and red bell pepper [44]; saskatoon berry [45]; cape gooseberry [33] and pomegranate arils [46].

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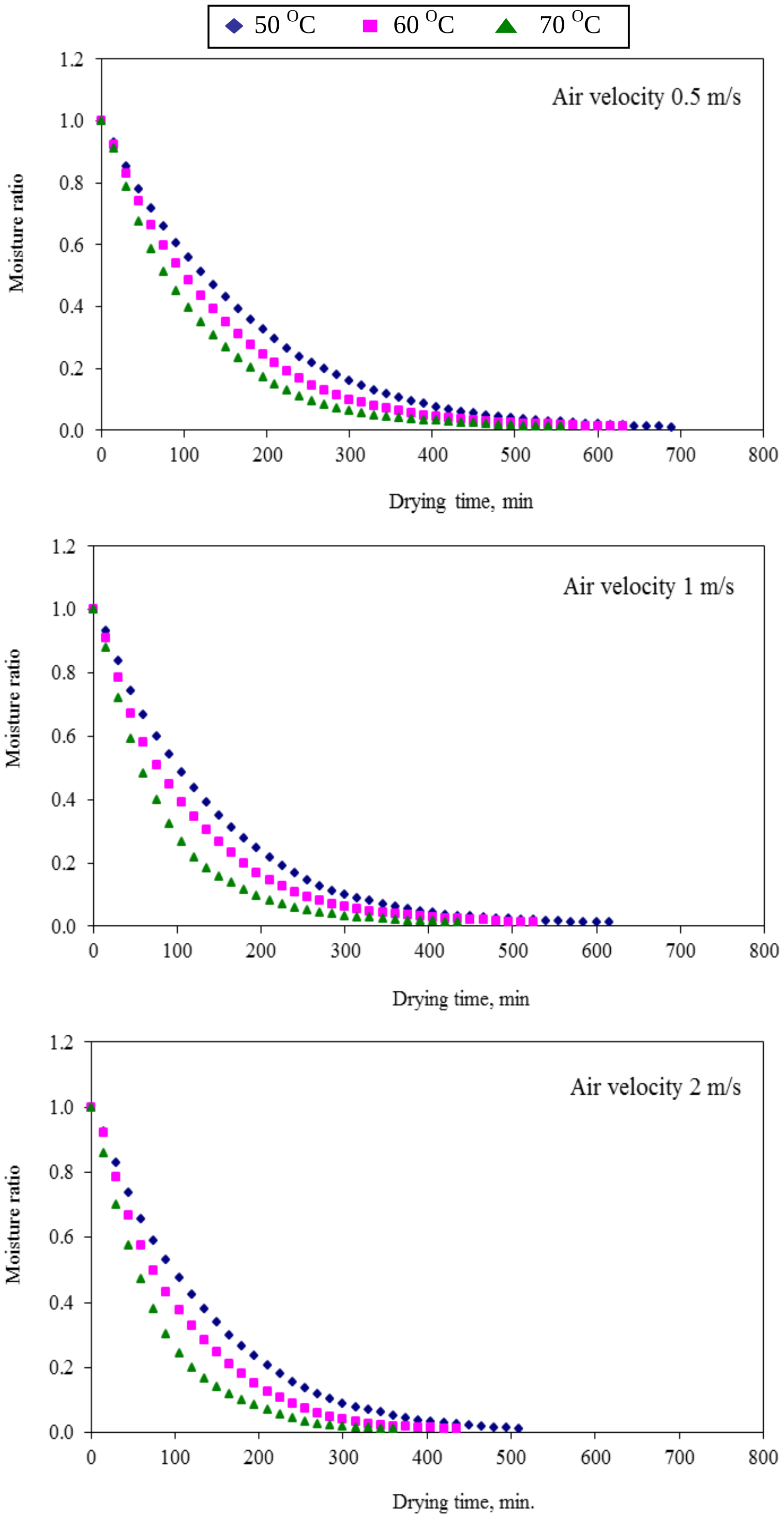


**Fig. 2:** Variation of moisture ratio of onion slices with drying time for the vertical convective hot-air dryer (HA) at different drying air temperatures and air velocities.

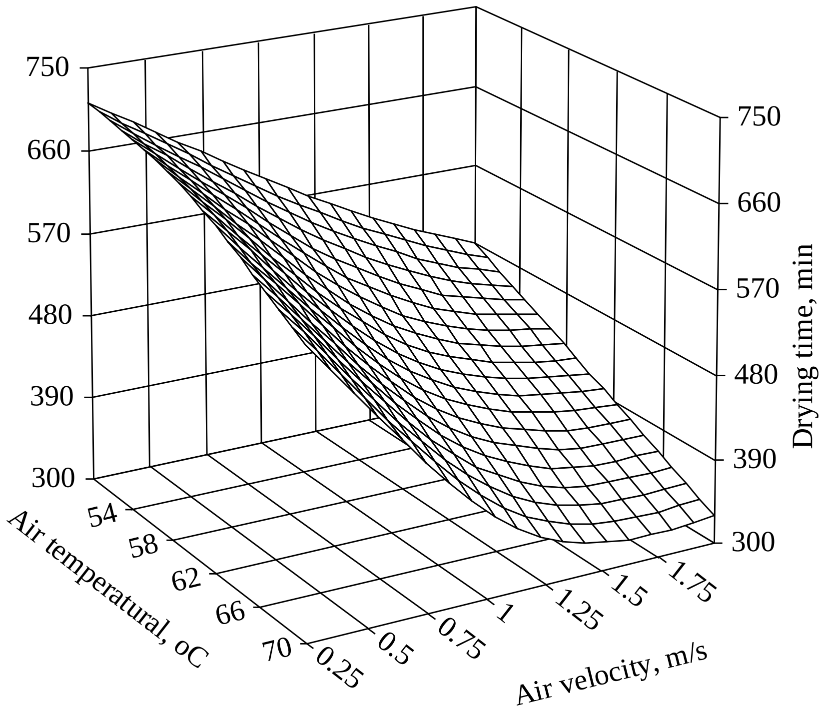


**Fig. 3:** Variation of drying time with drying air temperature and drying air velocity, while drying onion slices using convection hot-air dryer (HA).

**Table 2:** Average values of statistical parameters of selected models filled to thin-layer drying of onion slices under infrared (IR), convective (HA) and combined infrared and convective (IR-HA) drying.

| Model | Drying methods | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | HA | | | IR | | | IR-HA | | |
| | $R^2$ | EF | $\chi^2$ | $R^2$ | EF | $\chi^2$ | $R^2$ | EF | $\chi^2$ |
| Newton | 0.9931 | 0.9958 | 0.001810 | 0.9910 | 0.9908 | 0.00591 | 0.9985 | 0.99845 | 0.000611 |
| Henderson and Pabis | 0.9908 | 0.9914 | 0.000137 | 0.9890 | 0.9918 | 0.002031 | 0.9980 | 0.9914 | 0.002484 |
| Page | 0.9986 | 0.9962 | 0.000065 | 0.9871 | 0.9874 | 0.002817 | 0.9986 | 0.9905 | 0.009847 |
| Modified Page | 0.9844 | 0.9737 | 0.011504 | 0.9989 | 0.9975 | 0.003362 | 0.9886 | 0.9887 | 0.00018 |
| Logarithmic | 0.9985 | 0.9860 | 0.000067 | 0.9978 | 0.9985 | 0.005261 | 0.9988 | 0.9919 | 0.00074 |
| Two-term | 0.9866 | 0.9880 | 0.000069 | 0.9983 | 0.9908 | 0.001407 | 0.9986 | 0.9889 | 0.00254 |
| Modified Hend. & Pabis | 0.9989 | 0.9945 | 0.002270 | 0.9910 | 0.9983 | 0.002361 | 0.9989 | 0.9902 | 0.00058 |
| Midilli et al | 0.9991 | 0.9996 | 0.000038 | 0.9998 | 0.9994 | 0.000217 | 0.9997 | 0.9990 | 0.000084 |
| Verma et al | 0.9977 | 0.9870 | 0.000083 | 0.9930 | 0.9910 | 0.005141 | 0.9987 | 0.9785 | 0.000098 |
| Wang and Sing | 0.9956 | 0.9953 | 0.001084 | 0.9918 | 0.9938 | 0.002651 | 0.9906 | 0.9906 | 0.000198 |
| Thompson | 0.9594 | 0.9079 | 0.014658 | 0.9974 | 0.9956 | 0.000741 | 0.9404 | 0.9651 | 0.00099 |

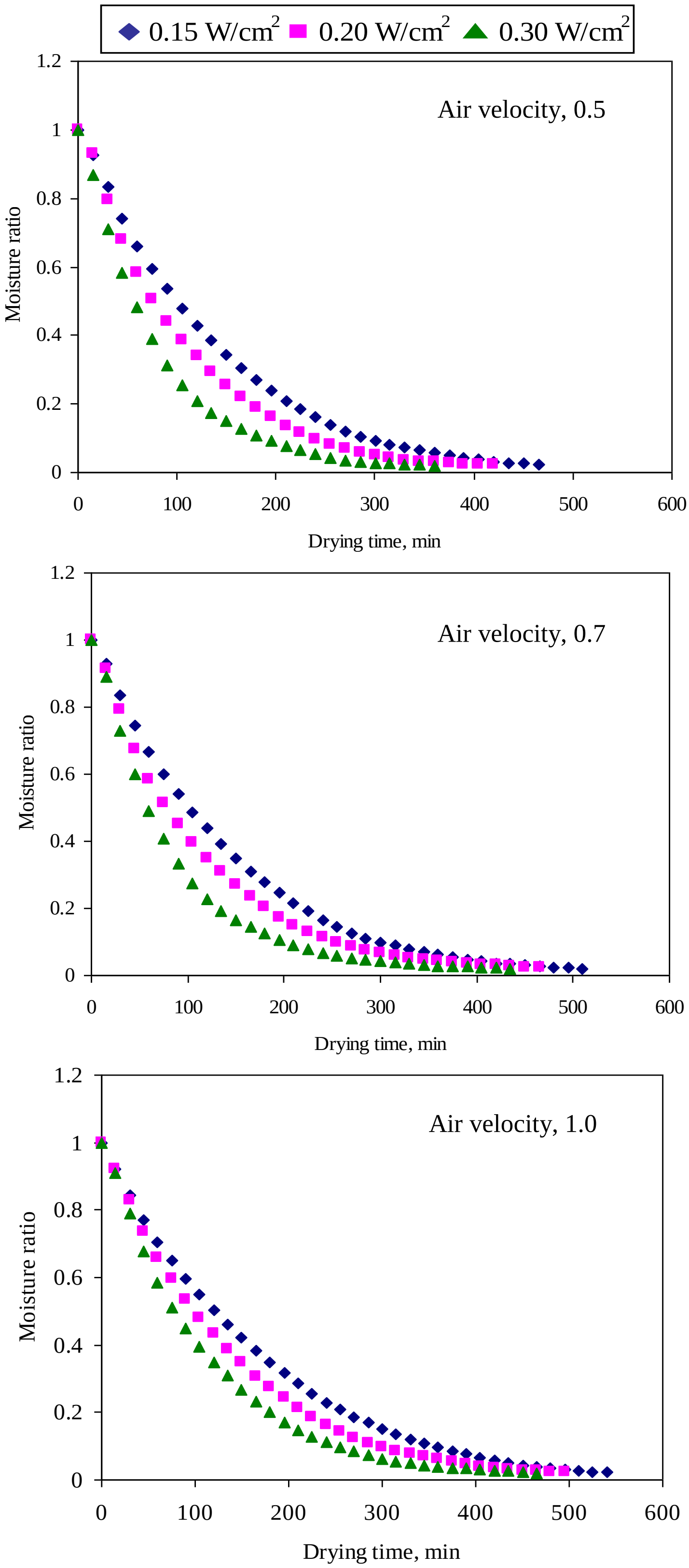


**Fig. 4:** Variations of moisture ratio of onion slices while drying at various radiation intensities and air velocities in the infrared dryer (IR).

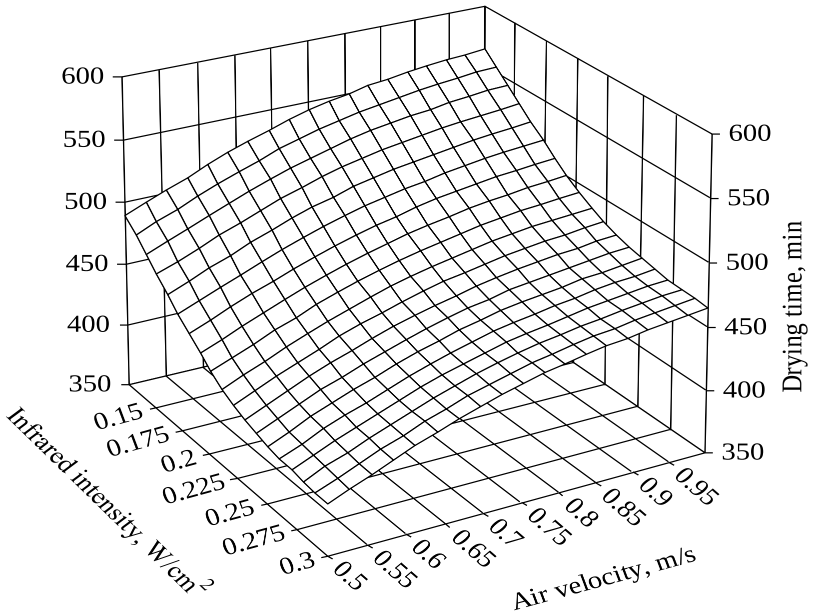


**Fig. 5:** Variation of infrared radiation intensity and air velocity with the drying time when drying onion slices in the infrared radiation dryer (IR).

Figure 8 is a plot of me- asured values of moisture ratio while drying onion slices in the (HA) dryer against values estimated using the Midili et al model. The model could estimate the drying behaviour of onion slices with good accuracy over the entire temperature and velocity range. Similar results have been reported by Meisami-asl et al., [47]. The drying constants (k) and (b) and coefficients (a) and (n) of the model and also the statistical variables of the goodness of fit are presented in Table 3.

**Table 3:** Statistical results of Midilli et al. model and its constant and coefficient at different drying temperatures and velocities of the convective hot-air dryer (HA).

| Air Temperature, °C | Air Velocity, m/s | k | a | n | b | $R^2$ | EF | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| MR = a exp(-kt$^n$) + bt | | | | | | | | |
| | | | | | | | | |
| 50 | 0.5 | 0.0069 | 0.871 | 1.099 | 0.0007 | 0.9998 | 0.9997 | 0.000033 |
| | 1.0 | 0.0075 | 0.899 | 1.067 | 0.0001 | 0.9945 | 0.9998 | 0.000031 |
| | 2.0 | 0.0080 | 0.998 | 1.025 | 0.0003 | 0.9998 | 0.9999 | 0.000033 |
| | | | | | | | | |
| 60 | 0.5 | 0.0073 | 0.999 | 1.093 | 0.00035 | 0.9997 | 0.9996 | 0.000048 |
| | 1.0 | 0.0085 | 1.013 | 1.038 | 0.00011 | 0.9999 | 0.9989 | 0.000047 |
| | 2.0 | 0.0093 | 1.033 | 1.042 | 0.00009 | 0.9997 | 0.9997 | 0.000047 |
| | | | | | | | | |
| 70 | 0.5 | 0.0099 | 0.887 | 1.124 | 0.00083 | 0.9986 | 0.9994 | 0.000033 |
| | 1.0 | 0.010 | 0.958 | 1.175 | 0.00015 | 0.9998 | 0.9995 | 0.000031 |
| | 2.0 | 0.011 | 1.018 | 1.055 | 0.00035 | 0.9998 | 0.9997 | 0.000038 |

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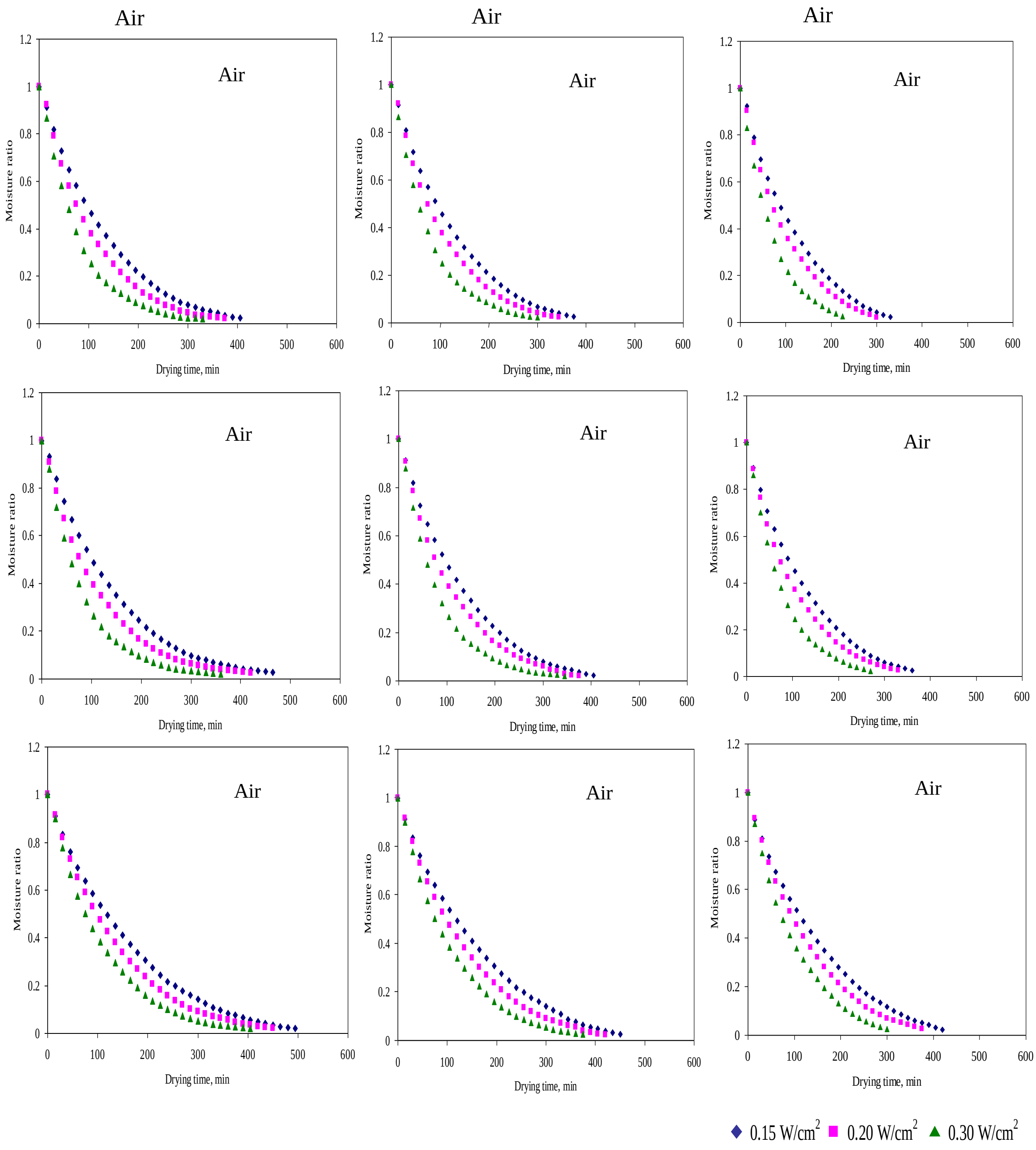


**Fig. 6:** Moisture ratio variation of onion slices under infrared radiation combined with hot-air convection drying process

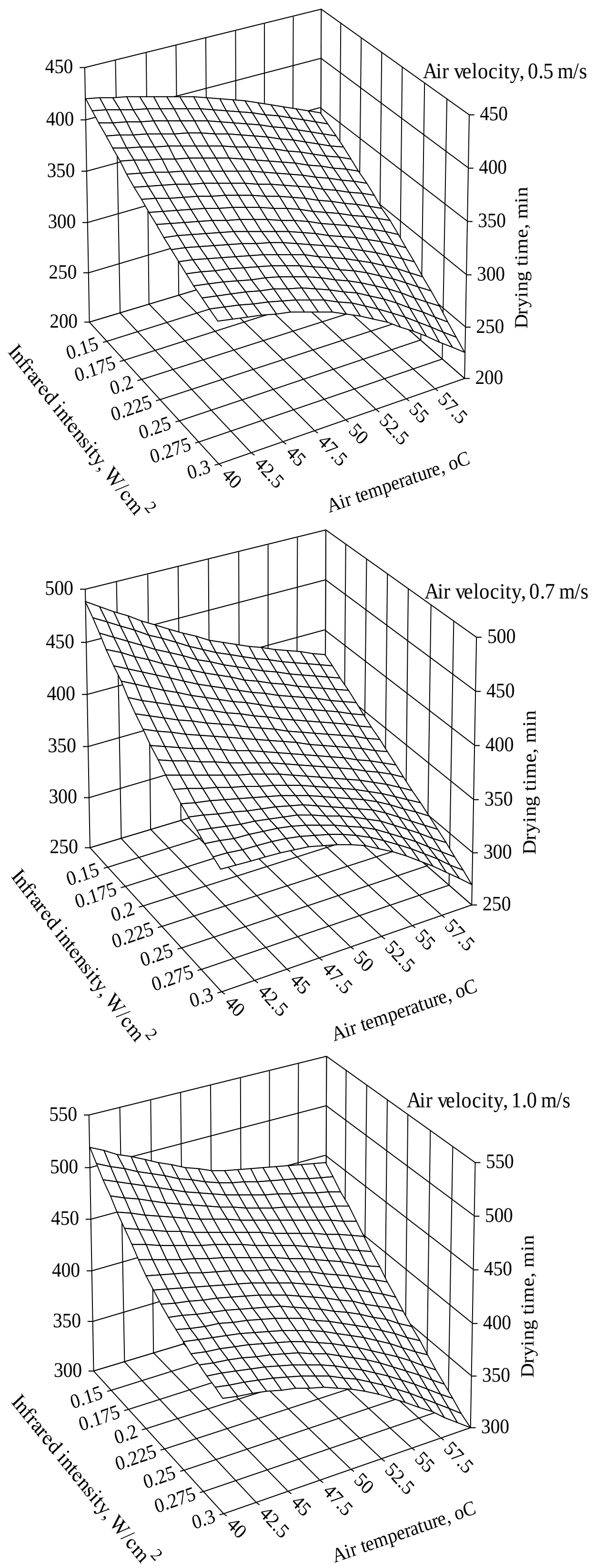


**Fig. 7:** Variation of drying time with drying applications using combined infrared and convection hot-air dryer (IR-HA).

The Midilli et al. model was also fitted to experimental data from the IR dryer collected over different infrared radiation intensities and air velocities. The drying constants (k) and (b) and coefficients (a) and (n) of the model and also the statistical variables of the goodness of fit are presented in Table 4. To take into account for the effect of the drying variables on the Midilli et al. model, the constant of k ($min^{-1}$) and each of the coefficients of a, n and b were each used in a multiple regression against infrared radiation intensity (*IR*) in $W/cm^2$ and drying air velocity (*V*) in m/s. The plotted responses in Fig. 9 demonstrates that the data points follows a straight line close to 45° angle signifying the suitability of the model in describing the thin layer infrared drying of the onion slices.

**Table 4:** Results of statistical analysis on Midilli et al. model at different infrared intensities and air velocities using infrared (IR) dryer.

| Infrared Intensity, $W/cm^2$ | Air Velocity, m/s | k | a | n | b | $R^2$ | EF | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| $MR = a \exp(-kt^n) + bt$ | | | | | | | | |
| | | | | | | | | |
| 0.15 | 0.5 | 0.0080 | 1.093 | 1.077 | 0.00005 | 0.9998 | 0.9998 | 0.00019 |
| | 0.7 | 0.0090 | 1.066 | 1.059 | 0.00047 | 0.9998 | 0.9996 | 0.00020 |
| | 1.0 | 0.0050 | 1.037 | 1.045 | 0.00091 | 0.9998 | 0.9998 | 0.00023 |
| | | | | | | | | |
| 0.20 | 0.5 | 0.0093 | 1.133 | 1.058 | 0.00008 | 0.9997 | 0.9996 | 0.00017 |
| | 0.7 | 0.0071 | 1.215 | 1.024 | 0.000085 | 0.9999 | 0.9998 | 0.00025 |
| | 1.0 | 0.0095 | 1.055 | 1.034 | 0.00076 | 0.9998 | 0.9986 | 0.00023 |
| | | | | | | | | |
| 0.30 | 0.5 | 0.0110 | 1.095 | 1.011 | 0.00415 | 0.9998 | 0.9998 | 0.00021 |
| | 0.7 | 0.0154 | 1.129 | 1.057 | 0.00018 | 0.9999 | 0.9979 | 0.00019 |
| | 1.0 | 0.0121 | 1.351 | 0.987 | 0.00037 | 0.9998 | 0.9998 | 0.00028 |

Table 5 shows the results of statistical analysis of $R^2$, EF, and $\chi^2$ of Midilli et al. model for various drying air temperatures, infrared intensity, air velocities and air temperatures, respectively for protect dried in the IR-HA dryer. The values of mentioned tests were in the range of 0.997-0.999 for $R^2$, 0.00006-0.000098 for $\chi^2$ and 0.998-0.999 for EF. Validation of the Midilli et al. model was confirmed by comparing the estimated or predicted moisture ratio at any particular drying condition. The validation of the Midilli et al. model at different air temperatures, air velocities and infrared intensities is presented in Fig. 10. The predicted data generally banded around the straight line which showed the suitability of the Midilli et al. model in describing the combined infrared and convection hot air (IR-HA) drying behaviour of the onion slices. This agrees with the work of other researchers such as Togrul [48] and Ruiz-Celma et al. [49].

*Conclusion:*

Onion slices were dried using three different drying methods, i.e., convection hot-air (HA), infrared radiation (IR) and combined infrared- convection hot air (IR-HA) drying. The influence of drying conditions for each dryer method on the drying kinetics of onion slices was investigated. Drying time increased with the increased in air velocity at all infrared intensity applied, however it reduced with increase in drying air temperature and infrared intensity under IR and combination (IR-HA) methods. Under hot air convection (HA) an increase in drying air velocity and an increase in air temperature shortened the drying time for all drying conditions. The most convenient drying methods for drying onion was the combined (IR-HA) with regard to drying rate and drying time. Statistical results for that thin-layer drying showed that, the Midilli et al. model given by [$MR = a.\exp(-k.t^n) + b.t$] represented the drying characteristics of onion slices better than eleven other frequently used thin layer drying models. For all the conditions studied, $R^2$ and EF values were higher than 0.998 and0.997, respectively and $\chi^2$ value were lower than 0.00007.

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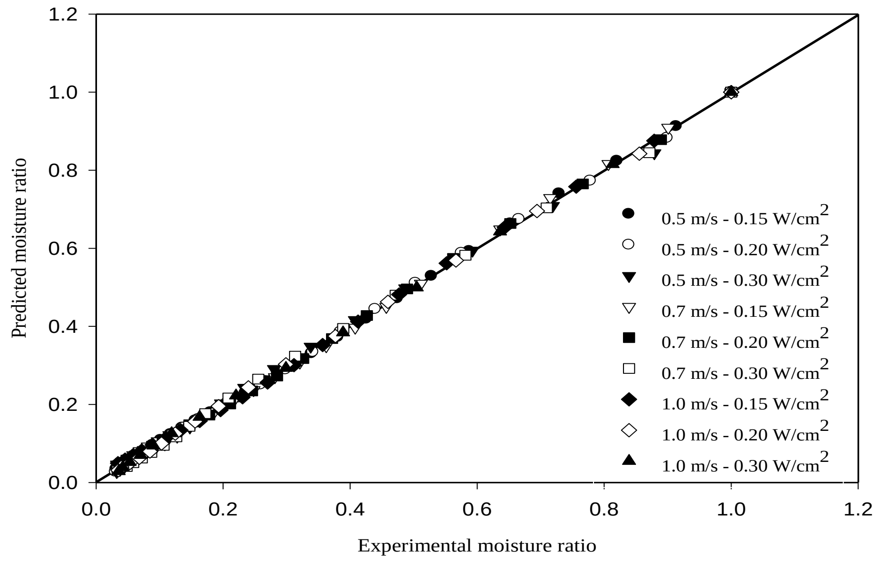


**Fig. 9:** Experimental and predicted moisture ratio using Midilli et al. model when drying conditions at infrared intensity and air velocity in the infrared (IR) dryer.

**Table 5:** Statistical results of Midilli et al. model and its constants and coefficients at different infrared intensities, air drying temperatures and air velocities using combination infrared with hot air dryer (IR-HA).

| Air velocity, m/s | Coefficients - Statistical parameters | 40 ºC | | | 50 ºC | | | 60 ºC | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.15 W/cm² | 0.2 W/cm² | 0.3 W/cm² | 0.15 W/cm² | 0.2 W/cm² | 0.3 W/cm² | 0.15 W/cm² | 0.2 W/cm² | 0.3 W/cm² |
| $MR = a \exp(-kt^n) + bt$ | | | | | | | | | | |
| | | | | | | | | | | |
| 0.5 | k | 0.0070 | 0.0090 | 0.0110 | 0.0131 | 0.0150 | 0.0092 | 0.0162 | 0.0181 | 0.0190 |
| | a | 1.961 | 1.591 | 1.323 | 1.117 | 1.109 | 1.014 | 1.009 | 0.993 | 1.011 |
| | n | 1.135 | 1.111 | 1.057 | 1.081 | 1.091 | 1.001 | 1.241 | 1.231 | 10.15 |
| | b | 0.00015 | 0.00017 | 0.00035 | 0.00055 | 0.0007 | 0.00016 | 0.0013 | 0.0009 | 0.0008 |
| | $R^2$ | 0.9998 | 0.9998 | 0.9978 | 0.9998 | 0.9997 | 0.9999 | 0.9987 | 0.9995 | 0.9998 |
| | EF | 0.999 | 0.9997 | 0.9998 | 0.9997 | 0.9995 | 0.9996 | 0.9997 | 0.9997 | 0.998 |
| | $\chi^2$ | 0.000097 | 0.00008 | 0.000067 | 0.000083 | 0.000081 | 0.00009 | 0.000081 | 0.00009 | 0.000078 |
| | | | | | | | | | | |
| 0.7 | k | 0.0051 | 0.0071 | 0.0080 | 0.0095 | 0.011 | 0.013 | 0.0091 | 0.0134 | 0.0161 |
| | a | 1.392 | 1.236 | 1.167 | 1.099 | 1.019 | 1.015 | 1.009 | 0.997 | 1.007 |
| | n | 1.010 | 1.051 | 1.053 | 1.076 | 1.011 | 1.031 | 1.023 | 0.998 | 1.013 |
| | b | 0.00005 | 0.00037 | 0.00019 | 0.00018 | 0.0005 | 0.00085 | 0.0002 | 0.0006 | 0.0009 |
| | $R^2$ | 0.9999 | 0.9997 | 0.9998 | 0.9997 | 0.9995 | 0.9996 | 0.9997 | 0.9997 | 0.9998 |
| | EF | 0.9998 | 0.9995 | 0.9997 | 0.9996 | 0.9996 | 0.9997 | 0.9998 | 0.9998 | 0.9998 |
| | $\chi^2$ | 0.000089 | 0.000099 | 0.000088 | 0.00008 | 0.000081 | 0.00009 | 0.00009 | 0.000079 | 0.00009 |
| | | | | | | | | | | |
| 1.0 | k | 0.0090 | 0.0084 | 0.011 | 0.0131 | 0.0151 | 0.0164 | 0.0172 | 0.0182 | 0.0198 |
| | a | 1.647 | 1.039 | 1.027 | 1.077 | 1.015 | 1.033 | 1.052 | 0.987 | 1.052 |
| | n | 1.362 | 1.156 | 1.114 | 1.079 | 1.018 | 1.091 | 0.969 | 1.163 | 1.252 |
| | b | 0.00004 | 0.00008 | 0.00078 | 0.00071 | 0.0009 | 0.00011 | 0.0006 | 0.0009 | 0.0002 |
| | $R^2$ | 0.9998 | 0.9995 | 0.9997 | 0.9996 | 0.9996 | 0.9997 | 0.9998 | 0.9998 | 0.9998 |
| | EF | 0.9998 | 0.9995 | 0.9997 | 0.9996 | 0.9996 | 0.9997 | 0.9998 | 0.9998 | 0.9998 |
| | $\chi^2$ | 0.000081 | 0.000079 | 0.000081 | 0.000083 | 0.00009 | 0.00008 | 0.000081 | 0.00009 | 0.000069 |

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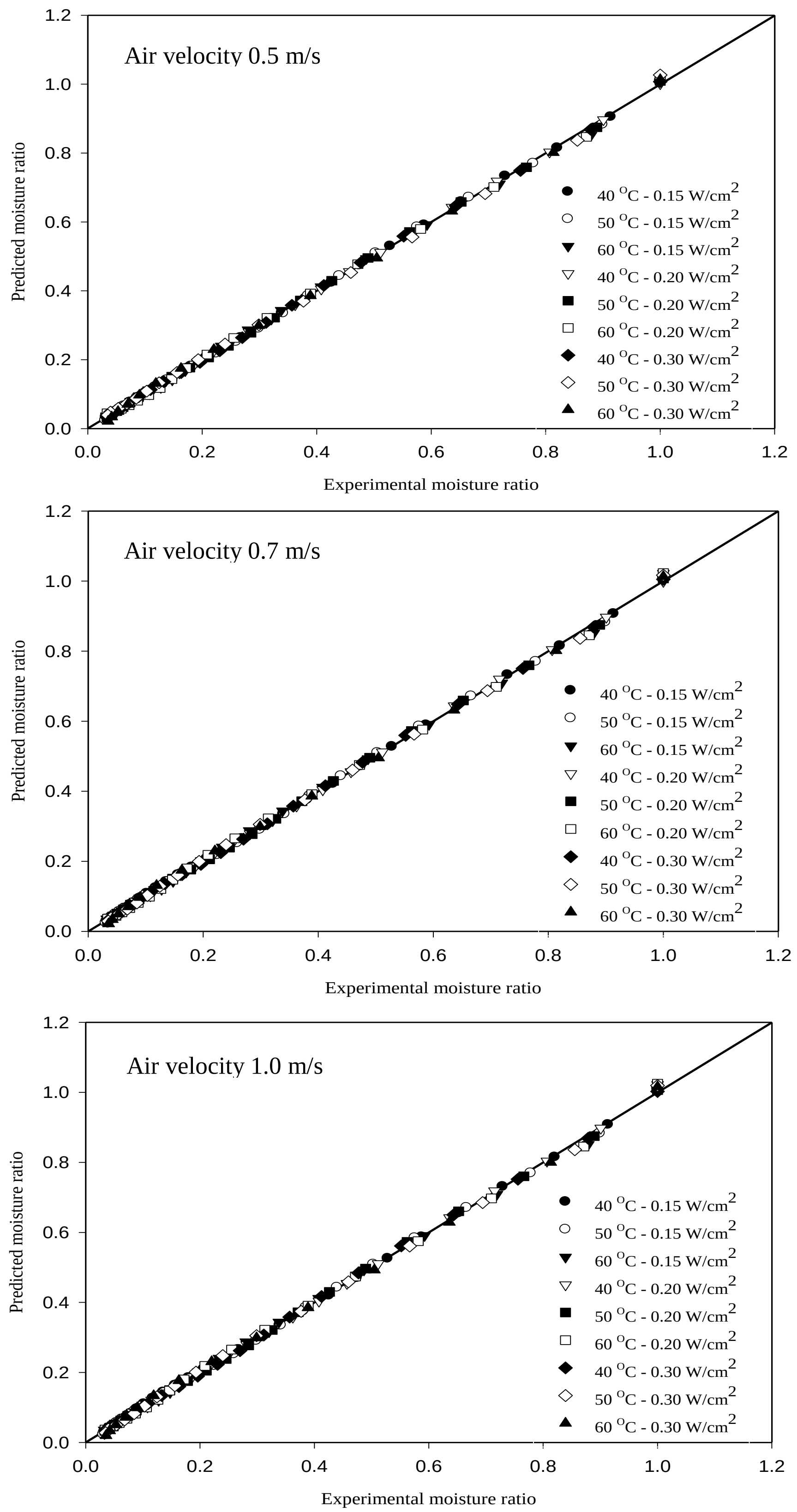


**Fig. 10:** Experimental and predicted moisture ratio using Midilli et al. model at different infrared intensities, air drying temperatures and air velocities using combination infrared with hot air dryer (IR-HA).

## REFERENCES

[1] Quiles, A., I. Hernando, I. Pe´rez-Munuera, V. Larrea, E. Llorca and M.A. Lluch, 2005. Polyphenoloxidase (PPO) activity and osmotic dehydration in Granny Smith apple. Journal of the Science of Food and Agriculture, 85(6): 1017-1020.
[2] Das, S., T. Das, P.S. Rao and R.K. Jain 2001. Development of an air recirculating tray dryer for high moisture biological materials. Journal of Food Engineering, 50: 223-227.
[3] Corzo-Martinez, M., N. Corzo and M. Villamiel, 2007. Biological properties of onions and garlic. Trends in Food Science & Technology, 18: 609-625.
[4] Kaymak-Ertekin, F., and A. Gedik, 2005. Kinetic modelling of quality deterioration in onions during drying and storage. Journal of Food Engineering, 68: 443-453.
[5] Leeratanarak, N., S. Devahastin and N. Chieechan, 2006. Drying kinetics and quality of potato chips undergoing different drying techniques. J. Food Eng.,77: 635-643.
[6] Caglar, A., I.T. Togrul and H. Togrul, 2009. Moisture and thermal diffusivity of seedless grape under infrared drying.Food Bioproducts Processing, 87: 292-300.
[7] Wanyo, P., S. Siriamornpun and N. Meeso, 2011. Improvement of quality and antioxidant properties of dried mulberry leaves with combined far-infrared radiation and air convection in Thai tea process. Food and Bioproducts Processing, 89: 22-30.
[8] Meeso, N., A. Nathakaranakule, T. Madhiyanon and S. Soponronnarit, 2008. Different strategies of far-infrared radiation application in paddy drying. International Journal of Food Engineering, 4: 1-30.
[9] Doymaz, I., 2012. Infrared drying of sweet potato (*Ipomoea batatas L.*) slices. Journal of Food Science and Technology, 49(6): 760-766
[10] Babalis, S., V. Belessiotis, 2004. Influence of drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs. Journal of Food Engineering, 65(3): 449-458.
[11] Mirzaee, E., S. Rafiee and A. Keyhani, 2010. Evaluation and selection of thin-layer models for drying kinetics of apricot (cv. NASIRY). Agric. Eng. Int: CIGR Journal, 12(2): 111-116.
[12] Purkayastha, M.D., A. Nath, B.C. Deka and C.L. Mahanta, 2013. Erratum to: Thin layer drying of tomato slices. J. Food Sci. Technol., 50: 654-654.
[13] Doymaz, I., 2007. Air-drying characteristics of tomatoes.Journal of Food Engineering, 78(4): 1291-1297.
[14] AOAC, 1990. Official methods of analysis (12th ed.), Association of Official Analytical Chemists. Washington, DC.
[15] EL-Mesery, H.S and G. Mwithiga, 2012. Comparison of a gas fired hot-air dryer with an electrically heated hot-air dryer in terms of drying process, energy consumption and quality of dried onion slices. African J. Agric. Res., 7(31): 4440-4452.
[16] Calin-Sanchez, A., K. Lech, A. Szumny, A. Figiel and A.A. Carbonll-Barrachina, 2012. Volatile composition of sweet basil essential oil (Ocimumbasilicum L.) as affected by drying method. Food Res. Int. 48: 217–225.
[17] Kingsly, R.P., R.K. Goyal, M.R. Manikantan and S.M. Ilyas, 2007. Effects of pretreatments and drying air temperature on drying behaviour of peach slice. International J. Food Sci. and Technol, 4: 65-69.
[18] Akgun, N.A and I. Doymaz, 2005. Modelling of olive cake thin-layer drying process. J. Food Eng, 68: 455-461.
[19] Doymaz, I., 2004. Convective air drying characteristics of thin layer carrots.Journal of Food Engineering 61: 359–364.
[20] Sharifian, F., A.M. Motlagh and A.M. Nikbakht, 2012. Pulsed microwave drying kinetics of fig fruit (Ficuscarica L.). Aust. J. Crop Sci., 6: 1441-1447.
[21] AmiriChayjan, R., K. Salari and H. Barikloo, 2012. Modelling moisture diffusivity of pomegranate seed cultivars under fixed, semi fluidized and fluidized bed using mathematical and neural network method. Acta Sci. Pol. Technol. Aliment. 11: 137-149.
[22] Ayensu, A., 1997. Dehydration of food crops using a solar dryer with convective heat flow. Solar Energy, 59: 121-126.
[23] Henderson, S.M., and S. Pabis, 1961. Grain drying theory I: temperature effect on drying coefficient. Journal of Agricultural Research Engineering, 6: 169-174.
[24] Page, G., 1949. Factor influencing the maximum rates of air drying shelled corn in thin layer. MS Thesis (unpublished), Purdue University.
[25] Ozdemir, M., and Y.O. Devres, 1999.The thin layer drying characteristics of hazelnuts during roasting. Journal of Food Engineering, 42: 225-233.
[26] Yagcioglu, A., 1999. Drying techniques of agricultural products.Ege. Univ., Faculty of Agriculture, Publication No: 536 Bornova, Izmir, Turey (in Turkish).
[27] Madamba, P.S., R.H. Driscoll and K.A. Buckle, 1996. The thin layer drying characteristics of garlic slices. Journal of Food Engineering, 29: 75-97.

[28] Wang, C.Y., and R.P. Singh, 1978. A single layer drying equation for rough rice.Transactions of the ASAE Paper No. 3001.
[29] Karathanos, V.T., 1999. Determination of water content of dried fruits by drying kinetics. Journal of Food Engineering, 39: 337-44.
[30] Midilli, A., H. Kucuk and Z. Yapar, 2002. A new model for single layer drying.Drying Technology, 20(7): 1503-13.
[31] Thomson, T.L., P.M. Peart and G.H. Foster, 1968. Mathematical simulation of corn drying: A new model. Transactions of the ASAE; 11: 582-6.
[32] Verma, L.R., R.A. Bucklin, J.B. Endan and F.T. Wratten, 1985. Effects of drying air parameters on rice drying models. Transactions of the ASAE, 28: 296-301.
[33] Vega-Galvez, A., L. Puente-Diaz, R. Lemus-Mondaca, M. Miranda and M.J. Torres, 2014. Mathematical Modeling of Thin-Layer Drying Kinetics of Cape Gooseberry (*PhysalisPeruviana L.*). Journal of Food Processing and Preservation, 38: 728-736.
[34] Mota, C.L., C. Lucianoa, A. Diasa, M.J. Barrocab and R.P.F. Guiné 2010. Convective drying of onion: Kinetics and nutritional evaluation. Food and Bioproducts Processing, 88: 115-123.
[35] Motevali, A., S. Minaei, M.H. Khoshtagaza and H. Amirnejat, 2011.Comparison of energy consumption and specific energy requirements of different methods for drying mushroom slices. Energy, 36: 6433-6441.
[36] Ponkham, K., and N. Meeso, S. Soponronnarit and S. Siriamornpun, 2011. Modelling of combined far-infrared radiation and air drying of a ring shaped-pineapple with/without shrinkage.Food and Bioproducts Processing, 90: 155-164.
[37] Lin, Y.P., T.Y. Lee, J.H. Tsen and V.A.E. King, 2007. Dehydrationof yam slices using FIR-assisted freeze drying. Journal of FoodEngineering, 79: 1295-1301.
[38] Afzal, T.M., and T. Abe, 2000. Simulation of moisture changes in barley during far infrared radiation drying. Computers and Electronics in Agriculture, 26: 137-145.
[39] Sharma, G.P., R.C. Verma and P. Pathare, 2005. Thin-layer infrared radiation drying of onion slices. Journal of Food Engineering, 67: 361-366.
[40] Khir, R., Z. Pana, A. Salimc, B.R. Hartsougha, S. Mohamedc, 2011. Moisture diffusivity of rough rice under infrared radiation drying. LWT - Food Science and Technology, 44: 1126-1132.
[41] Jaturonglumlert, S., and T. Kiatsiriroat, 2010. Heat and mass transfer in combined convective and far-infrared drying of fruit leather. Journal of Food Engineering, 100(2): 254-260.
[42] Motevali, A., S. Minaei, M.H. Khoshtaghaza, M. Kazemi and A.M. Nikbakht, 2010. Drying of Pomegranate Arils: Comparison of Predictions from Mathematical Models and Neural Networks. Int. J. Food Eng., 6(3): 1-20.
[43] Kocabiyik, H., and D. Tezer, 2009. Drying of carrot slices using infrared radiation. Int J Food Sci Technol, 44: 953-959.
[44] Schössler, K., H. Jäger and D. Knorr, 2012. Effect of continuous and intermittent ultrasound on drying time and effective diffusivity during convective drying of apple and red bell pepper. J. Food Eng., 108: 103-110.
[45] Reddy, L., 2006. Drying characteristics of saskatoon berries under microwave and combined microwave-convection heating. MS Thesis. Canada: University of Saskatchewan.
[46] Mundada, M., B.S. Hathana and S. Maske, 2010. Convective dehydration kinetics of osmotically pretreated pomegranate arils. Biosystems engineering, 107: 307-316.
[47] Meisami-asl, E.S., A. Rafiee, Keyhani and A. Tabatabaeefar, 2010. Determination of suitable thin layer drying curve model for apple slices (variety-Golab). Plant Omics Journal, 3(3): 103-108.
[48] Togrul, H., 2006. Suitable drying model for infrared drying of carrot. Journal of Food Engineering, 77: 311-323.
[49] Ruiz-Celma, A., F. López-Rodríguez and F. Cuadros Blázquez, 2009.Characterisation of industrial tomato by-products from infrared drying process.Food Bioproducts Processing, 87: 282-291.