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Convective Drying of Tomato Slices: Evaluation of the Mass and Moisture Transport Parameters of Thin-Layer Drying

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ABSTRACT

In this study, the evaluation of moisture and mass transport parameters of hot air drying of tomato slices was investigated at air temperatures of 60°C, 80°C, 100°C and 120°C for samples of 3 to 11 mm thickness using a convective air dryer. Using the experimental data, the objective of this study is to determine the transport parameters (lag factor, drying constants, moisture diffusivities and convective mass transfer coefficient) for tomato slices subjected to convection drying. The analyzed drying data were obtained in the period of decreasing drying rate. Regarding the results of moisture and mass transport parameters, the drying coefficient of tomato varied from 3.83×10^{-5} s^{-1} to 3.067×10^{-4} s^{-1} under our air-drying conditions. The lag factor of tomato slices ranged from 1.0791 to 1.1070. The mass Biot number values for tomato slices were in the range of 0.5586 to 0.9379. The effective moisture diffusivity for tomato slices ranged from 3.90×10^{-10} to 1.06×10^{-8} m^2/s, for our drying conditions. The convective mass transfer coefficient values for tomato slices were in the range of 2.98×10^{-7} to 1.04×10^{-6} m/s. The activation energy for moisture diffusion was 28.203 kJ/mol, 27.488 kJ/mol, 29.433 kJ/mol, 31.844 kJ/mol and 32.668 kJ/mol, respectively for tomato thicknesses of 3 mm, 5 mm, 7 mm, 9 mm and 11 mm. For the same tomato thicknesses of 3 mm, 5 mm, 7 mm, 9 mm and 11 mm, the activation energy for convective mass transfer was 36.717 kJ/mol, 35.977 kJ/mol, 38.047 kJ/mol, 40.550 kJ/mol and 41.206 kJ/mol, respectively.

1. INTRODUCTION

Tomato (Lycopersicon esculentum) cultivation is widely spread throughout the world. Tomato fruits are currently regarded as one of the world's major vegetable crops. They have a significant economic impact on the earnings of many growers worldwide. The tomato fruit is one of the most widely grown vegetables in the world and is ranked second in many nations. The majority of varieties of tomato fruits have higher moisture content, ranging from 80 to 90%. This moisture content value is significantly higher than what is needed for extended preservation. The effects of bacteria, enzymes, and yeast are slowed down in these crops when their moisture content is reduced to a certain degree. So, moisture content in tomato fruits is decreased to a suitable level for storage and handling using the drying (Gameh et al., 2024). Drying involves two fundamental and simultaneous processes: the transfer of heat to evaporate the liquid and the transfer of mass as a liquid or vapor within the solid and as a vapor from the surface. During the drying process, moisture transfer occurs in two main stages: external mass transfer, which involves the evaporation of moisture from the product's surface into the surrounding air and internal mass transfer, which refers to the movement of moisture from inside the product towards its surface (Fernandes and Tavares, 2024).Throughout history, different drying methods of tomatoes have been developed to speed up the drying process and maintain the product's nutritious content (Lamesgen and Abeble, 2022). These drying methods include hot air convective drying (Abioye et al., 2024; Conte et al., 2024), spouted bed drying (Chada et al., 2022) , solar drying (Ahmed et al., 2024; El-Sheikha et al., 2024; Elwakeel et al., 2024), microwave drying (Alvi et al., 2023; Nwankwo et al., 2022), conductive drying (Kilicli et al., 2023; Qiu et al., 2019) , vacuum drying (Gul et al., 2024), freeze drying (Nzimande et al., 2024), spray drying (Anisuzzaman et al., 2023), infrared drying methods (Obajemihi et al., 2025) . Moreover, hot air drying, using the heated air to extract moisture from wet tomatoes, is one of some of the popular methods of thin layer drying tomatoes for stockage and preservation. Because it is economical, adaptable, and readily integrable with other processing systems (Kilic et al., 2024). That is why, numerous studies have been conducted over time to investigate the hot air drying of tomato in different types and/or shapes for helping to prolong the shelf life of tomato. As example, the hot air-drying process of tomato slices was studied at air temperatures of 40 to 80 °C for thicknesses of 4 to 8 mm. For this tomato shape, the hot air drying of tomato generally took place during the period of decreasing drying

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rate under these drying conditions (Elfar, 2022; Khama et al., 2022). With the period of decreasing drying rate of tomatoes, moisture transfer inside the tomato body occurs mainly by molecular diffusion captured globally by effective moisture diffusivity. The values of effective moisture diffusivity for tomatoes were determined using the solution proposed by Crank with the assumption of neglected external resistances on the slab shapes of tomato samples (Guemouni et al., 2022). Effective moisture diffusivity values of tomatoes determined for the infinite slab geometry were reported during drying at air temperatures of 45 to 100 °C and for sample thicknesses of 5 to 10 mm (Guemouni et al., 2022; Obajemihi et al., 2021). The diffusivity values for the spherical tomatoes were found in hot air drying at drying temperatures of 50 to 80 °C and for samples of 11 to 14 cm in diameter using the analytical solution proposed by Crank for spherical products (Bennamoun et al., 2015). In addition to the effective moisture diffusivity, the heat and mass transfer coefficients were estimated for solar drying of tomato slices with 4–6 mm thicknesses using the thermodynamics (Lingayat et al., 2021). Although there are a large number of studies available in the literature on hot air drying of tomato, to the best of our knowledge, there are few studies conducted to determine the moisture transfer parameters using lag factor and drying coefficient during the hot air-drying process of tomato slices considering the internal and external moisture resistances. Using the experimental data from literature, the objective of this study is to determine the transport parameters (lag factor, drying constants, moisture diffusivities and moisture transfer coefficient) for tomato slices subjected to air convection drying.

2. EXPERIMENTAL DATA

Experimental data on the variation of moisture content of tomato slices reported by Khazaei et al. (2008) (Khazaei et al., 2008) were used to determine the drying process parameters and the mass transfer parameters of tomato slices. The researchers dried tomato slices (cut into circular disks of 3 mm, 5 mm, 7 mm, 9 mm and 11 mm thickness), with an initial moisture content of 94.4% (wet basis, wb) until the final moisture content reached 15% (wb), using a pilot-type air dryer at air temperatures of 60, 80, 100 and 120 °C). For more details on drying tomato slices in the convection drying process, see Khazaei et al. (2008) (Khazaei et al., 2008).

3. DRYING THEORY

3.1 Moisture content

The moisture content was calculated as follows:

$$X(t) = \frac{m(t) - m_s}{m_s} \qquad (1)$$

Where X(t) is dry-based moisture content (d.b.) expressed in kg $_{water}$/kg $_{dry\ matter}$; m (t), mass of the wet product, expressed in kg at time t and m_s, dry matter mass of sample (kg).

3.2 Moisture ratio

The moisture ratio (MR) was calculated from the mass loss data of samples during drying. Equation (2) was used to calculate the moisture ratio (Metwally et al., 2024):

$$\mathbf{MR} = \frac{\overline{X}(t) - X_e}{X_0 - X_e} \qquad (2)$$

Where X, X_0 and X_e are respectively mean moisture content at any time of drying (kg $_{water}$/kg $_{dry\ matter}$), initial mean moisture content (kg $_{water}$/kg $_{dry\ matter}$) and equilibrium moisture content (kg $_{water}$/kg $_{dry\ matter}$).

As Xe is much lower than X_0 and X, it is negligible in this study. Then moisture ratio becomes:

$$\mathbf{MR} = \frac{\overline{X}}{X_0} \qquad (3)$$

3.3 Moisture transport analysis

Moisture transport during drying of most foods is accomplished by moisture diffusion (liquid and/or vapor). The moisture diffusion process observed during food drying is similar to the transient heat conduction process in these wet solid objects. Assuming the isotropic property of the drying samples with respect to moisture diffusivity, Fick's second law of unsteady state diffusion governing the process is of the same form as the Fourier equation for heat transfer, in which temperature and thermal diffusivity are replaced by moisture and moisture diffusivity, respectively. This law, used to describe moisture migration in the drying process, is as follows (Yamchi et al., 2024):

$$\frac{\partial X}{\partial t} = Div[\mathbf{D}_{\mathbf{eff}}(gradX)] \qquad (4)$$

Where D_{eff} is effective moisture diffusivity of wet product (m^2 /s) and *t* is drying time (s).

To evaluate the drying process parameters (e.g., drying coefficient and lag factor) and determine the mass transfer parameters (e.g., effective moisture diffusivity and convective mass transfer coefficient) of tomato slices during hot air convection drying at different thickness and air temperature levels, Equation (4) is used under certain assumptions. These assumptions include: (a) the primary moisture content is uniform; (b) the solid maintains its shape and volume; (c) the thermophysical properties of the solid and the drying medium are constant; (d) the effect of heat transfer on moisture loss is negligible; (e) moisture diffusion occurs in one direction following the thickness; and (f) there are finite internal and external resistances to moisture transfer in the solid. Under these conditions, equation (4) in cartesian coordinate system and in dimensionless form can be written as a function of the thickness direction (*x*) as follows (Man et al., 2024b):

$$\frac{\partial \phi}{\partial t} = \mathbf{D}_{\mathbf{eff}} \frac{\partial^2 \phi}{\partial x^2} \qquad (5a)$$

$$\phi(x,t) = \frac{X(x,t) - X_e}{X_0 - X_e} \qquad (5b)$$

The initial and boundary conditions for solving equation (5) are (Costa et al., 2018):

$$\phi(x,t) = 1, \quad t = 0, \qquad -L \le x \le +L \qquad (6a)$$

$$\frac{\partial \phi(x,t)}{\partial x} = 0, \quad t > 0, \qquad x = 0 \qquad (6b)$$

$$-\mathbf{D}_{\mathbf{eff}} \frac{\partial \phi(x,t)}{\partial x} = \mathbf{h}_{\mathbf{m}} \phi_s, \quad t > 0, \qquad x = \mp L \qquad (6c)$$

Where h_m is convective moisture transfer coefficient of wet product *(m /s)*, *x* and L are respectively the cartesian coordinate from the symmetry axis and the half-thickness for the slab *(m)*.

The solution of the governing equation (i.e., equation (5)) under the initial and boundary conditions given in equation (6), with *x= 0*, gives dimensionless transient mean moisture ratio distributions for drying sliced tomato samples in the form of series solutions as follows (Polatoğlu and Aral, 2022):

$$MR = \frac{\overline{X}(t)}{X_0} = \sum_{n=1}^{\infty} A_n B_n \qquad (7a)$$

where A_n and B_n are defined as follows (Ferreira et al., 2020):

$$\begin{cases} A_n = \dfrac{2 \sin \mu_n}{\mu_n + \sin \mu_n \cos \mu_n} \\ B_n = exp(-\mu_n^2 Fo) \end{cases}$$

$$\text{for } 0.1 < \mathrm{Bi}_m < 100 \qquad (7b)$$

Where μ_n is the nth root of the transcendental (dimensionless) characteristic equation; Bi_m and Fo are respectively the Biot number and the Fourier number for moisture transport which, for a slab of thickness 2L, are defined as:

$$Bi_m = \frac{h_m L}{D_{eff}} \quad (8a)$$

$$Fo = \frac{D_{eff} t}{L^2} \quad (8b)$$

The above form of the series solutions can be simplified if the values of $F_o > 0.2$ are negligible. Thus, the infinite sum of equation (7) is well approximated by the first term only that is (Rajoriya et al., 2021):

$$MR = A_1 B_1$$

where

$$\begin{cases} A_1 = G = \dfrac{2\sin\mu_1}{\mu_1 + \sin\mu_1\cos\mu_1} = \exp\left(\dfrac{0.2533 Bi_m}{1.3 + Bi_m}\right) \\ B_1 = \exp(-\mu_1^2 Fo) \end{cases}$$

$$\text{for } 0.1 < Bi_m < 100 \quad (9)$$

The root μ_1 of the transcendental characteristic equation is given for the slab product as follows (Al-Hilphy et al., 2021):

$$\mu_1 = \arctan(0.640443 Bi_m + 0.380379)$$

$$\text{for } 10 < Bi_m < 100 \quad (10)$$

In equation (9), G represents the lag factor (dimensionless) and is obtained by regressing the dimensionless values of moisture ratio (MR) and drying time in the exponential form of the equation below using the least squares curve fitting method (Golpour et al., 2021):

$$MR = G\exp(-St) \quad (11)$$

Where S represents the drying coefficient (s^{-1}). The drying coefficient S shows the drying capacity of tomato per unit time and the lag factor G is an indication of the internal resistance of sliced tomato samples to moisture transfer during convection drying. These parameters are useful for evaluating the drying process of tomato samples.

Both equations (9) and (11) are in the same form and can be equated. Therefore, having $A_1 = G$ and replacing the Fourier number (Fo) and B_1 with their expressions in equations (8) and (11), the moisture diffusivity for tomato samples is given in the following form (Malakar et al., 2022):

$$D_{eff} = \frac{SL^2}{\mu_1^2} \quad (12)$$

The expression of the moisture transfer coefficient (h_m) for drying of sliced tomato samples is obtained using the Biot number (Bi_m) as defined by the following equation (Kaya et al., 2010):

$$h_m = \frac{D_{eff} Bi_m}{L} = \frac{D_{eff}}{L}\left(\frac{1 - 3.94813\ln G}{5.1325\ln G}\right) \quad (13)$$

To determine the mass transport parameters for drying sliced tomato samples, the following procedure was applied (Golpour et al., 2021):

a. Using the least squares curve fitting method, the moisture ratio values and drying time were regressed as equation (11) and the lag factor (G) and drying coefficient (S) were determined.
b. The Biot number was calculated using equation (9).
c. The value of μ_1 was determined from equation (10).
d. Moisture diffusivity was calculated using equation (12).
e. The moisture transfer coefficient was obtained from equation (13).

3.4 Activation energy

Effective moisture diffusivity can be linked to air temperature by Arrhenius type expression (Feng et al., 2024), such as:

$$D_{eff} = D_0 \exp\left[-\frac{E_{a-d}}{\mathcal{R}(T + 273.15)}\right] \quad (14)$$

Where D_0 is the constant of the Arrhenius type equation (m^2/s), $E_{a\text{-}d}$ is the activation energy for moisture diffusion (J/mol), T is the uniform temperature of the sliced product (°C) and $\mathcal{R}$=8, 3145 is the universal gas constant (J/mol K). Equation (14) can be rearranged into the form:

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_{a-d}}{\mathcal{R}(T + 273.15)} \quad (15)$$

Also, a similar procedure can be adopted to describe the convective mass transfer coefficient (h_m) depending on the temperature following an Arrhenius type equation (Golpour et al., 2021):

$$h_m = h_{m0} \exp\left[-\frac{E_a}{\mathcal{R}(T + 273.15)}\right] \quad (16)$$

$$\ln(h_m) = \ln(h_{m0}) - \frac{E_{a-c}}{\mathcal{R}(T + 273.15)} \quad (17)$$

where h_{m0} is a constant (m/s) and $E_{a\text{-}c}$ is the activation energy for convective mass transfer (J/mol).

3.5 Statistical analysis

Four statistical parameters were used to determine the ability of the tested model to represent the experimental data, namely: the coefficient of determination (R^2), the root mean square error (RMSE), the reduced chi-square (χ^2) and the sum of squared errors (SSE) (Yamchi et al., 2024):

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(P_{exp,i} - P_{pre,i})^2}{\sum_{i=1}^{N}(\bar{P}_{exp} - P_{exp,i})^2} \quad (18)$$

$$RMSE = \left[\frac{\sum_{i=1}^{N}(P_{exp,i} - P_{pre,i})^2}{N}\right]^{1/2} \quad (19)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(P_{exp,i} - P_{pre,i})^2}{N - z} \quad (20)$$

$$SSE = \sum_{i=1}^{N}(P_{exp,i} - P_{pre,i})^2 \quad (21)$$

Where P is the hot air-drying parameter, $P_{exp,i}$ is the experimental value of the parameter, $P_{pre,i}$ is the value of the parameter P predicted by the statistical model, $\bar{P}_{exp,i}$ is the average value of the parameter P, N is the number of experimental observations and z is the number of constant coefficients in the model regression. A good fit of the drying model is found for the highest values of R^2 and for the lowest values of RMSE, χ^2 and SSE (Compaoré et al., 2022).

4. RESULTS AND DISCUSSION

4.1 Moisture ratio data fitting

Understanding the mass and moisture parameters of tomato slices requires the prediction of tomato drying kinetics by thin-layer models. In the literature, an analysis of the convection drying behaviour of tomato samples revealed the presence of periods of decreasing drying rates regardless of the drying conditions. In these drying periods, the most widely used approach to determine the mass transfer was the Crank solution of Fick's second law with the assumption of neglected external resistances (Obajemihi et al., 2025). However, this assumption situation is not validated provided that the moisture movement is governed by the internal and external moisture resistances. Consequently, in the current work, the moisture transport approach, which considers both external and internal diffusion mechanisms, is adopted to determine the process and mass transport parameters of tomato slices under hot air drying. The experimental moisture content values of dried tomato slices at air temperatures of 60 to 120 °C for slice thicknesses of 3 to 11 mm were converted to dimensionless moisture ratio using Equation (2). The curve fitting tool of MATLAB R2023b (MathWorks, Inc., Natick, MA) and the nonlinear regression technique were applied to fit the moisture content data to the exponential model (Equation (11)). Then, the statistical parameters, including the root mean square error (RMSE), the correlation coefficient (R^2), and the sum of squared errors (SSE), were used to evaluate the goodness-of-fit of the exponential model.

Table **1** shows the statistical results obtained by fitting the experimental moisture ratio data with the exponential model. In this table, the obtained values of R^2, RMSE and SEE show that the exponential model is satisfactorily fitted to the drying data for the different drying conditions used with higher R^2 values (0.9733-0.9899), lower RMSE values (0.0298-0.0520) and lower SSE values (0.0850-0.2683).

The drying curve (moisture ratio versus drying time) in which the falling rate period was located was well described by the exponential model at temperatures of 60 - 120°C and for tomato slices of 3 -11 mm thickness. This compatibility of experimental values and MR values calculated from the thin-layer model is illustrated in **Figure 1** for drying temperatures of 60°C and 120°C. Our results were in agreement with the fitting of drying data from the literature. Thus, when analysing the convection drying kinetics of celery in a single layer (5 mm thick), a good fit between the experimental moisture content of celery and that predicted by this thin-layer model was obtained for drying temperatures of 40 to 80 °C, with higher R^2 (0.9798–0.9904) and lower RMSE (0.0299–0.044) values (Rudy et al., 2024). Ayonga et al. (2023) fitted the experimental moisture content of orange-fleshed sweet potato slice drying to this model to study the effects of different pretreatments on thin-layer drying kinetics in a solar dryer. They found that this thin-layer model provided an acceptable fit to the solar drying conditions of sweet potato slices with statistical results such as R^2 = 0.7834-0.9727 and RMSE = 0.0688-0.1079 (Ayonga et al., 2023). For refractive window drying of mint (Mentha spicata L.) leaves, the experimental MR values obtained for convection drying of leaves followed a typical trend of this model, producing an adequate fit with the coefficient of determination (R^2) values found to be greater than 0.90 and with an average value of 0.9929 for all experimental conditions at water temperature levels of 50 to 90°C (Kaveh et al., 2024).

4.2 Drying process parameters

Using the method of fitting the experimental data of the moisture content with the exponential model as described in the previous section, the drying process parameters such as the drying coefficient (S) and the lag factor (G) were determined for tomato slices with thicknesses of 3 to 11 mm at air temperatures of 60 to 120 °C. Their values with the corresponding statistical parameters are presented in

Table **1**. As shown in the results in

Table **1**, the drying coefficient of tomato which shows the ability of its tomato slices to dry per unit time ranged from 3.83×10^{-5} s^{-1} to 3.067×10^{-4} s^{-1} under our hot air-drying conditions. The values obtained in this paper are comparable to the values reported in the drying literature for some foods such as oyster mushroom slices (S=1.4686 $\times 10^{-4}$ s^{-1}) obtained during hot air drying at air temperatures of 50–75 ◦C and for rectangular pieces of 26 × 13 × 26 mm (Nadew et al., 2024), two varieties of mango seeds (9.5627 $\times 10^{-5}$–6.395 $\times 10^{-3}$ s^{-1}) obtained during convection drying at air temperatures of 40–80 °C (Gebre et al., 2024) and walnut (1.666 $\times 10^{-5}$–3.716 $\times 10^{-4}$ s^{-1}) calculated for an hot air drying at air temperatures of 50–80 °C (Man et al., 2024a).

Furthermore, the lag factor of tomato slices was an indicator of the magnitude of internal and external resistance of these wet products to moisture transfer during the convection drying process. Regarding the hot air-drying process of tomato sliced samples and as shown in the results in Table 1, the retardation factor (G) of tomatoes ranged from 1.0791 to 1.1070. Its lag factor values were between 1 and 1.2732 for drying infinite slab objects, which led to moisture Biot numbers between 0.1 and 100. This range was known as the most common case for food drying applications (Polatoğlu and Aral, 2022). Our lag factors indicated that moisture diffusion in tomato samples was controlled by both internal and external resistance (all greater than 1). Moreover, this variation in the calculated values, ranging from 1.0791 to 1.1070, reflects the system-specific mass transport characteristics of this tomato variety grown worldwide. The lag factor values obtained in this study are consistent with the results reported for oyster mushrooms cut into rectangular pieces of 26 × 13 × 26 mm with G = 1.076 (Nadew et al., 2024), avocado peels with G obtained in the range of 1.0621 to 1.2148 (Razola-Díaz et al., 2023) and orange peels with G ranging from 1.062 to 1.290 (Razola-Díaz et al., 2023).

4.3 Mass transfer Biot number (Bi_m)

The Bi_m is an important dimensionless parameter in food drying such as hot air drying of tomato slices. It explains the relationship between the internal moisture diffusion resistance inside tomato slices and the convective resistance of external moisture to its surfaces. It can also be used to calculate the internal mass diffusion rate in tomato slices. In this study, the Bi_m values of tomato slices are determined at drying air temperatures of 60 to 120 °C and sample thicknesses of 3 to 11 mm (Table 2). The calculated Bi_m values for sliced tomatoes ranged from 0.5586 to 0.9379. This range was in the case where $0.1<Bi_m<100$ for the common drying application case (Rajoriya et al., 2021). It indicates the presence of external and internal resistances to moisture diffusion and mass transfer of tomato slices. The Bi_m values obtained for these tomatoes were closer to 0.1, indicating that the effect of internal resistance on mass transfer was of the same order of physical magnitude as that of external mass resistance and was also comparatively higher than that of this external resistance. The Bi_m values obtained in this study were of the same order of magnitude as those reported by other works in the literature. The Bi_m estimated for Jatropha seeds, which were in the range 0.152 - 0.86, were greater than 0.1, implying the presence of finite internal and external resistances to moisture diffusion in Jatropha seeds during its drying (Agbede et al., 2024). Golpour et al. (2022) calculated the Bi_m for mass transfer of rice samples for air temperatures ranging from 30 to 80 °C and at air velocity range from 0.5 to 3.5 m s-1 (Golpour et al., 2021). These authors reported Bi_m values ranging from 0.043 to 0.2026. These values are significantly lower than those found in the present study. Therefore, the external resistance to mass transfer would be significant with Bi_m below 100, and thus the effective moisture diffusivity would also be affected by external drying conditions. These data demonstrate the significant presence of external and internal mass transfer parameters during the drying of tomato slices.

4.4 Moisture transfer parameters

Moisture diffusion is the rate of transfer of water molecules in moist foods to different directions per unit time.

This phenomenon of moisture diffusion of foods during drying is a very complicated mechanism. Varietal theories, thermal and molecular diffusion, hydrodynamic flow, etc., have been proposed to explain the moisture diffusion in these foods. The effective moisture diffusivity (D_{eff}), which combines these various diffusion theories, is the most important parameter to control and improve the mass transport process during food drying (Bassey et al., 2024). Knowledge of moisture diffusivities for foods is still important, as more complex mathematical models and correlations that can provide a deeper understanding of drying processes require data on D_{eff} (Costa et al., 2018). D_{eff} values of tomato slices were calculated at air temperatures of 60–120 °C for thicknesses of 3–11 mm and the results are listed in Table 2. In this table, the D_{eff} values for sliced tomatoes ranged from 3.90×10^{-10} to 1.06×10^{-8} m^2/s, for our drying conditions. These results are within the range of 10^{-12}– 10^{-8} m^2/s for food drying (Sun et al., 2024). This magnitude of D_{eff} is similar to those of previous food drying work, namely the ranges of 1.86×10^{-10} to 2.75×10^{-9} m^2/s and 3.32×10^{-10} to 3.87×10^{-9} m^2/s, respectively for convection drying of pelleted foods for pigs and calves at air temperatures ranging from 20°C to 70°C and air velocities ranging from 0.5 to 2.0 m/s (Wang et al., 2024) and the range 5.29×10^{-9} - 9.40×10^{-9} m^2/s for graphene far infrared drying of corn (Jibril et al., 2024). However, the D_{eff} values obtained in this study were higher than those found for solar drying dates, which ranged from 7.14×10^{-12} to 2.17×10^{-11} m^2/s (Metwally et al., 2024) and for drying pretreated eggplant slices by microwave with a range of 5.95×10^{-10} – 9.56×10^{-10} m^2 /s (Salehi et al., 2024). This D_{eff} variability came from internal and external drying conditions in these works which were different to those employed in our paper. Moreover, the moisture transfer between the interface of the drying food and the hot air is an important mass phenomenon and is described by a mass convective transfer coefficient (h_m). This coefficient represents the rate of moisture transport from the food surface to the air stream during convective drying. The h_m values of tomato slices were calculated at air temperatures of 60–120 °C for sample thicknesses of 3–11 mm based on D_{eff}, Bi_m and L values. The h_m values for tomato slices ranged from 2.98×10^{-7} to 1.04×10^{-6} m /s (Table 2). These results are in the comparable range of those reported by some authors for different foods and drying conditions, such as those reported for drying at 80 – 140°C of Jatropha seeds ranging from 3.160×10^{-7} to 4.812×10^{-6} m/s (Agbede et al., 2024) and those reported for drying of burdock root slices ranging from 1.3256×10^{-7} to 7.8375×10^{-7} m/s (Nguyen et al., 2023).

4.5 Activation energy of mass transfer and moisture diffusion

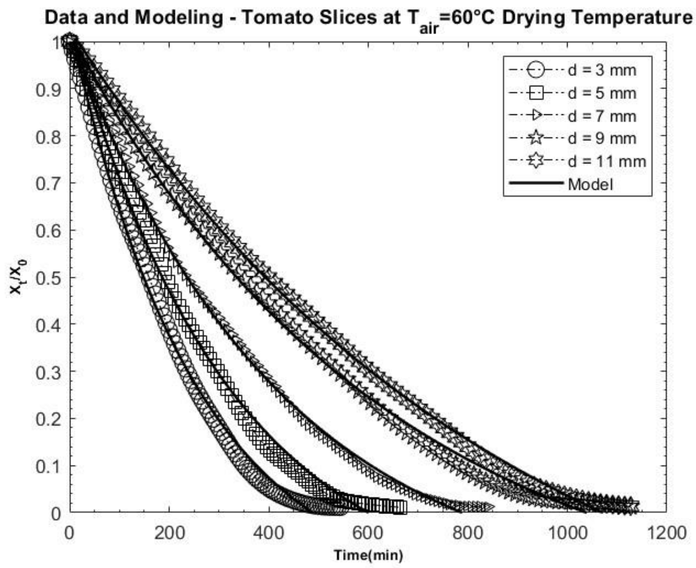
For engineering applications, it is useful to obtain Arrhenius functions that describe the effect of air temperature on D_{eff} and h_m. The Arrhenius functions expressing the evolution of D_{eff} and h_m for tomato slices as a function of air temperature are evaluated by least-squares fitting of the drying data in Table 2 as ln (D_{eff}) and ln(h_m) to the inverse of the absolute air temperature, using equations (15) and (17) respectively. The natural logarithm of D_{eff} and h_m for tomato slices 3–11 mm thick was plotted against the inverse of the absolute air temperature as shown in Figure 2. In this figure, the values of the activation energy for moisture diffusion (E_{a-d}) and for convective mass transfer (E_{a-c}) are obtained from the different slopes of the curves. The E_{a-d} value reflects the sensitivity of D_{eff} to hot air temperature, indicating the energy required to initiate water diffusion for drying tomato slices. The results of activation energy with their statistical parameters of tomato slices are presented in Table 3. The E_{a-d} values obtained for tomato were 28.203 kJ/mol, 27.488 kJ/mol, 29.433 kJ/mol, 31.844 kJ/mol and 32.668 kJ/mol, respectively for thicknesses of 3 mm, 5 mm, 7 mm, 9 mm and 11 mm with R^2 (0.9687–0.9976), RMSE (0.0421–0.1663) and SSE (0.0035–0.0553). For the same thicknesses of 3 mm, 5 mm, 7 mm, 9 mm and 11 mm, the E_{a-c} values were 36.717 kJ/mol, 35.977 kJ/mol, 38.047 kJ/mol, 40.550 kJ/mol, and 41.206 kJ/mol with R^2 (0.9758–0.9952), RMSE (0.0766–0.1857), and SSE (0.0117–0.0689), respectively (Table 3). Our E_{a-d} values are in the range of 12.70–110.00 kJ/mol for most agricultural products (Butwong et al., 2025). The E_{a-d} values calculated in the present study were comparatively close to the activation energies of other works, namely the range of 24.11- 25.38 kJ/mol for 2-3 cm thick silage paper mulberry subjected to hot air drying (Xu et al., 2024). The E_{a-d} values of 36.74–41.43 kJ/mol and 37.49–42.91 kJ/mol were found for drying ripe and unripe bitter melon slices (Yamchi et al., 2024). Moreover, our E_{a-c} values of 36.717 kJ/mol, 35.977 kJ/mol, 38.047 kJ/mol, 40.550 kJ/mol and 41.206 kJ/mol obtained respectively for tomato thicknesses of 3 mm, 5 mm, 7 mm, 9 mm and 11 mm, are similar to the E_{a-c} values form the literature. For instance, the hot air and refractometer window drying processes of blueberry pulp resulted in an E_{a-c} value of 40.15 kJ/ mol (Rurush et al., 2022). The E_{a-c} values for convective dehydration of Jatropha seeds were estimated in the range of 16.1–26.8 kJ/mol (Agbede et al., 2024).

5. CONCLUSION

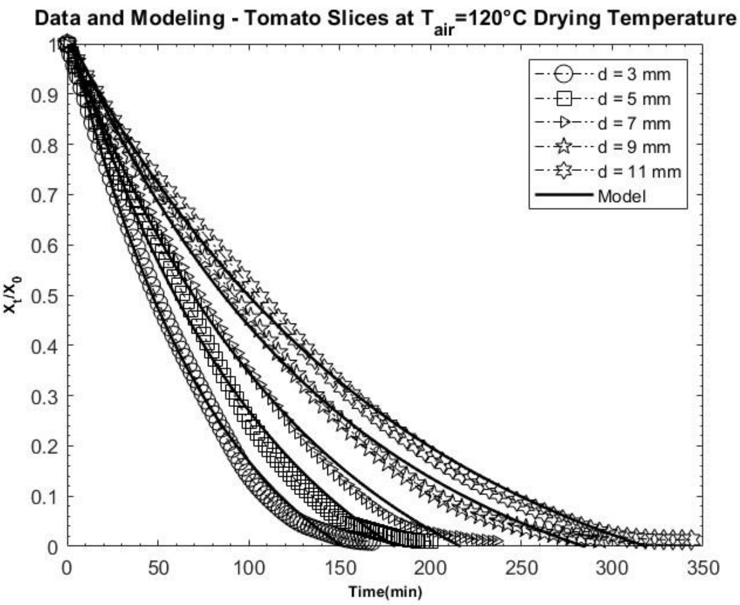
The evaluation of mass and moisture transport parameters of tomato slices was studied at air temperatures of 60°C, 80°C, 100°C and 120°C for samples of 3 to 11 mm thickness using a convection oven dryer. Using drying data of tomato slices, the objective of this study is to determine the transport parameters (lag factor, drying constants, moisture diffusivities and mass transfer coefficient) for tomato slices subjected to hot air drying. In the experiments, according to the data used for the study, the drying process occurred during the decreasing drying rate period for all air temperatures and tomato thicknesses. Regarding the results of mass and moisture transport parameters, the drying coefficients of tomato ranged from 3.83×10^{-5} s^{-1} to 3.067×10^{-4} s^{-1} under our air-drying conditions. The lag factor of tomato ranged from 1.0791 to 1.1070. The calculated values of mass Biot number for tomato slices ranged from 0.5586 to 0.9379. The effective moisture diffusivity for tomato slices ranged from 3.90×10^{-10} to 1.06×10^{-8} m^2/s, under our drying conditions. The values of convective mass transfer coefficient for tomato slices ranged from 2.98×10^{-7} to 1.04×10^{-6} m/ s. The activation energy for moisture diffusion was 28.203 kJ/mol, 27.488 kJ/mol, 29.433 kJ/mol, 31.844 kJ/mol and 32.668 kJ/mol, respectively for tomato thicknesses of 3 mm, 5 mm, 7 mm, 9 mm and 11 mm. For the same tomato thicknesses of 3 mm, 5 mm, 7 mm, 9 mm and 11 mm, the activation energy for convective mass transfer was 36.717 kJ/mol, 35.977 kJ/ mol, 38.047 kJ/ mol, 40.550 kJ/mol and 41.206 kJ/mol, respectively. The results of this study could be used as input data in the model simulation of drying process of tomato slices. In perspective, the study could be intended to extend to the mass and thermal parameters during drying of tomatoes in thick layers.

Table 1: Drying coefficient (S) and lag factor (G), MR = G exp(−St), for hot air drying of tomato slices drying at different temperatures and for five sample thickness

Temperature (°C)	Thickness (mm)	Model coefficients		Statistical parameters		
		G (-)	S(s^{-1})	R^2	RMSE	SEE
60	3	1.1070	9.83×10^{-5}	0.9776	0.0462	0.2094
	5	1.1080	7.83×10^{-5}	0.9779	0.0458	0.2056
	7	1.1093	6.00×10^{-5}	0.9819	0.0406	0.1632
	9	1.1100	4.33×10^{-5}	0.9753	0.0477	0.2094
	11	1.1120	3.83×10^{-5}	0.9714	0.0520	0.2489
80	3	1.0954	1.400×10^{-4}	0.9757	0.0491	0.2358
	5	1.0960	1.183×10^{-4}	0.9812	0.0428	0.1795
	7	1.0970	9.67×10^{-5}	0.9824	0.0399	0.1563
	9	1.0980	9.00×10^{-5}	0.9839	0.0384	0.1457
	11	1.0998	6.00×10^{-5}	0.9800	0.0419	0.1735
100	3	1.0820	2.467×10^{-4}	0.9834	0.0375	0.1113
	5	1.0830	1.817×10^{-4}	0.9899	0.0298	0.0877
	7	1.0847	1.483×10^{-4}	0.9890	0.0311	0.0850
	9	1.0860	1.400×10^{-4}	0.9837	0.0394	0.1523
	11	1.0933	1.300×10^{-4}	0.9826	0.0412	0.1667
120	3	1.0791	3.067×10^{-4}	0.9812	0.0422	0.1832
	5	1.0799	2.450×10^{-4}	0.9733	0.0510	0.2683
	7	1.0803	2.100×10^{-4}	0.9787	0.0442	0.2015
	9	1.0804	1.717×10^{-4}	0.9803	0.0402	0.1678
	11	1.0807	1.450×10^{-4}	0.9789	0.0442	0.1445



(a)

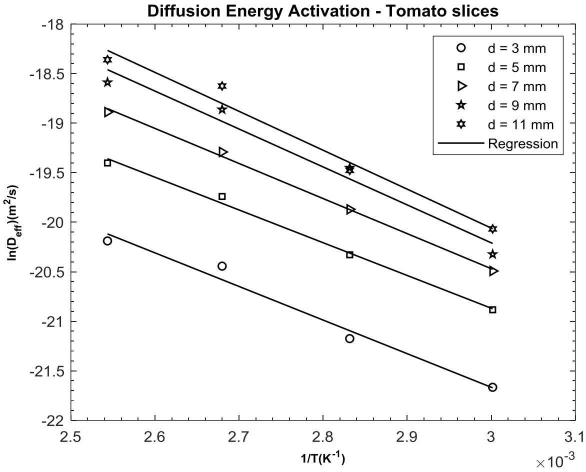


(b)

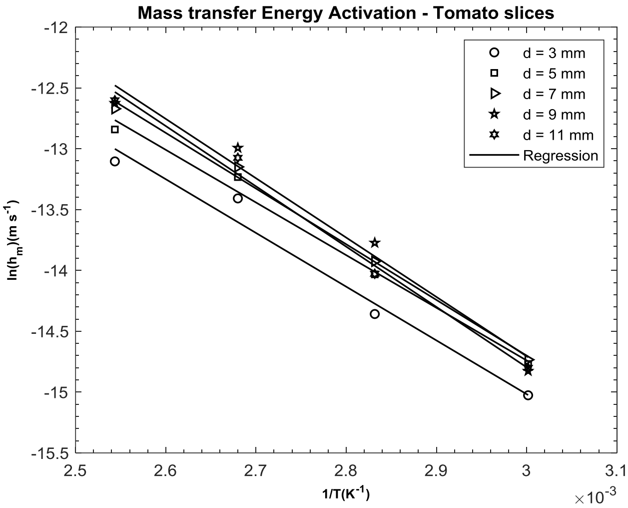
Figure 1: Experimental and predicted average moisture ratio of tomato slices at (a) 60°C air temperature and (b) 120°C air temperature for 3-11 mm thick samples.

Table 2: Mass transfer parameters calculated for the different drying conditions.

Temperature (°C)	Thickness(mm)	Bi_m (-)	μ_1(-)	D_{eff} ($m^2 s^{-1}$)	h_m ($m s^{-1}$)
60	3	0.8714	0.7537	3.90×10^{-10}	2.98×10^{-7}
	5	0.8844	0.7581	8.50×10^{-10}	3.85×10^{-7}
	7	0.9016	0.7638	1.26×10^{-9}	3.99×10^{-7}
	9	0.9109	0.7670	1.49×10^{-9}	3.64×10^{-7}
	11	0.9379	0.7759	1.93×10^{-9}	3.73×10^{-7}
80	3	0.7304	0.7034	6.40×10^{-10}	5.81×10^{-7}
	5	0.7373	0.7060	1.48×10^{-9}	8.05×10^{-7}
	7	0.7488	0.7103	2.35×10^{-9}	8.96×10^{-7}
	9	0.7605	0.7145	3.57×10^{-9}	1.04×10^{-6}
	11	0.7819	0.7223	3.48×10^{-9}	8.09×10^{-7}
100	3	0.5872	0.6476	1.32×10^{-9}	1.50×10^{-6}
	5	0.5972	0.6517	2.67×10^{-9}	1.79×10^{-6}
	7	0.6145	0.6587	4.19×10^{-9}	1.94×10^{-6}
	9	0.6279	0.6640	6.43×10^{-9}	2.27×10^{-6}
	11	0.7067	0.6945	8.15×10^{-9}	2.09×10^{-6}
120	3	0.5586	0.6359	1.71×10^{-9}	2.03×10^{-6}
	5	0.5664	0.6391	3.75×10^{-9}	2.64×10^{-6}
	7	0.5703	0.6407	6.27×10^{-9}	3.13×10^{-6}
	9	0.5713	0.6411	8.46×10^{-9}	3.28×10^{-6}
	11	0.5743	0.6423	1.06×10^{-8}	3.36×10^{-6}



(a)



(b)

Figure 2: Representation by the Arrhenius-type equation for drying tomato slices: (a) of moisture diffusivity; (b) convective mass transfer coefficient

Table 3: Activation energy for the moisture diffusion and the convective mass transfer of tomato slices.

	Moisture diffusion				Convective mass transfer			
Thickness(mm)	**E_{a-d} (kJ/mol)**	**R^2**	**RMSE**	**SSE**	**E_{a-c} (kJ/mol)**	**R^2**	**RMSE**	**SSE**
3	28.203	0.9780	0.1229	0.0302	36.717	0.9761	0.1670	0.0558
5	27.488	0.9945	0.0596	0.0071	35.977	0.9902	0.1041	0.0217
7	29.433	0.9976	0.0421	0.0035	38.047	0.9952	0.0766	0.0117
9	31.844	0.9687	0.1663	0.0553	40.550	0.9758	0.1857	0.0689
11	32.668	0.9750	0.1519	0.0461	41.206	0.9906	0.1164	0.0271

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