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Influence of Air Temperature and Slice Thickness on the Mass and Moisture Transport Parameters of Thin-layer Drying of Tomato Slices

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ABSTRACT

In this study, the influence of drying parameters such as air temperature and sample thickness on the mass and moisture transport parameters of hot air drying of tomato slices were investigated at 60-120°C air temperatures for 3-11 mm thickness samples. Using the experimental data in literature, the aim of this study is to determine the influence of air temperature and samples thickness on the moisture and mas transport parameters for tomato slices subjected to drying. Concerning the influence results, the drying coefficient of tomatoes increased with increasing drying temperature whatever the employed sample thickness. At almost all air temperatures, reducing the tomato thickness caused the drying coefficient to increase. The increase in air temperature and decrease in sample thickness decreased the lag factor values. The Biot number values decrease with increase in the air temperature for all sample thickness. When sample thickness increases, the Biot number values increased also whatever drying air temperature. Moisture diffusivity values increased with increased air temperature from 60°C to 120°C and increased tomato sample thickness from 3 to 11 mm. The activation energy values for moisture diffusion and convective mass transfer were decreased with increasing samples thickness for all drying conditions applied.

Keywords: drying coefficient, lag factor, moisture diffusivity and convective mass transfer coefficient

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 (Duan 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 (Boateng, 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 (Conte et al., 2024; Salaudeen et al.,2024), spouted bed drying (Chada et al., 2022) , solar drying (Adeosun et al., 2024; Hikmatov et al., 2024; Rulazi et al., 2024), microwave drying (Engin and Kuşçu, 2023; Hussein et al. 2023;), conductive drying (Ibraheem and Bakori, 2024) , vacuum drying (Li et al., 2022), freeze drying (Bakir et al., 2023; Costa et al., 2023), spray drying (Anisuzzaman, et al., 2023), infrared drying methods (Bayana and İçier, 2024). 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 on recent literature, 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. 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. The drying process of tomato slices generally took place during the period of decreasing drying rate under all drying conditions. The drying rate curves also show the absence of a period of constant drying rate in the whole drying process of tomato slices. In addition, the period of decreasing drying rate for tomatoes being dried could be followed by another period of decreasing drying rate due to the phenomenon of product cementation (Al-Hilphy et al., 2021 ; Hussein et al., 2021). 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. Moisture diffusivity during drying is used to indicate moisture flux in the tomato sample. Moisture diffusivity of tomatoes is influenced by moisture content, distance from heat source, temperature, and thickness of tomato samples. These values for tomato were generally obtained by solving a differential equation formulated by Fick's second law of diffusion in an unsteady state. Moisture diffusivity for tomatoes was determined using the solution proposed by Crank with the assumption of neglected external resistances according to the slab and sphere shapes of tomato samples (Abano et al., 2014). Effective moisture diffusivity values of tomatoes determined for the slab geometry were reported during drying at temperatures of 45 to 100 °C and for thicknesses of 4 to 10 mm (Afifah et al., 2022; Elwakeel et al., 2024). These diffusivity values for the spherical shape of 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 (Cheng 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 on the influence of drying process variables on 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 investigate the influence of air temperature and slice thickness on the mass and moisture transport parameters (lag factor, drying constants, moisture diffusivities and moisture transfer coefficient) for tomato slices subjected to air convection drying.

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).

Drying Theory

Moisture content

The moisture content was calculated as follows:

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

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

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):

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

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

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

$$\mathrm{MR} = \frac{\overline{X}}{X_0} \tag{3}$$

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):

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

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., 2024):

$$\frac{\partial \phi}{\partial t} = \mathrm{D}_{\mathrm{eff}} \frac{\partial^2 \phi}{\partial x^2} \tag{5a}$$

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

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

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

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

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

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):

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

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

$$\begin{cases} A_n = \dfrac{2 \sin \mu_n}{\mu_n + \sin \mu_n \cos \mu_n} & \text{for } 0.1 < \mathrm{Bi}_m < 100 \\ B_n = exp(-\mu_n^2 Fo) & \end{cases} \tag{7b}$$

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

$$Bi_m = \frac{h_m L}{\mathrm{D}_{\mathrm{eff}}} \tag{8a}$$

$$Fo = \frac{\mathrm{D}_{\mathrm{eff}} t}{L^2} \tag{8b}$$

The above form of the series solutions can be simplified if the values of Fo > 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):

$$MR = A_1 B_1 \text{ where } \begin{cases} A_1 = G = \dfrac{2\sin\mu_1}{\mu_1 + \sin\mu_1 \cos\mu_1} = \exp\left(\dfrac{0.2533 Bi_m}{1.3 + Bi_m}\right) \text{ for } 0.1 < \mathrm{Bi}_m < 100 \\ B_1 = \exp(-\mu_1^2 Fo) \end{cases} \quad (9)$$

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

$$\mu_1 = arctan(0.640443 Bi_m + 0.380379) \text{ for } 10 < \mathrm{Bi}_m < 100 \quad (10)$$

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):

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

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

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

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).

Activation energy

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

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

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:

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

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):

$$\mathrm{h_m} = \mathrm{h_{m0}} \exp\left[-\frac{\mathrm{E_{a-c}}}{\mathcal{R}(\mathrm{T} + 273.15)}\right] \tag{16}$$

So,

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

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

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) (Feng et al., 2024).

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

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

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

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

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).

Results and Discussion

Moisture ratio data fitting

Understanding the drying physics 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 is 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 transfer approach, which considers both external and internal diffusion mechanisms, was 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 equation is satisfactorily fitted to the experimental 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). Agbede et al. (2024) analysed the moisture transfer properties of Jatropha curcas L. seeds. In this analysis, fitting the experimental moisture content of Jatropha seeds to this exponential model gave satisfactory results. The R^2 values of 0.9912 to 0.9986 coupled with low SSE (0.0018 - 0.0023) and RSME (0.0422 - 0.0479) values showed that the experimental data fit well with this exponential model (Agbede et al., 2024).

Influence of temperature and thickness on drying process parameters

Using the method of fitting experimental moisture content data with the exponential model as described in the previous section, the drying process parameters such as drying coefficient (S) and dimensionless retardation factor (G) were determined for tomato slices with thickness of 3–11 mm at air temperatures of 60–120 °C. Their values with corresponding statistical parameters are shown in **Table 1**. As shown in the results in **Table 1**, the tomato drying coefficient 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. Some factors such as native properties, initial and final moisture content of the product, drying method and drying conditions can affect the drying parameters of food materials. In our case and with the results in **Table 1**, the drying coefficient of tomato slices increases with increasing drying air temperature, regardless of the sample thicknesses used in this study. An increase in drying air temperature results in an increase in heat and mass transfer between the hot air and the sliced tomato samples and, consequently, a greater drying capacity of these tomatoes. Our results were consistent with the influence of drying air temperatures on drying coefficients (S) in the literature. Wang et al. (2024) reported the same results in terms of drying temperature on the convection drying coefficient of pelleted feed for growing pigs and calves at air temperatures of 10 to 50 °C. The drying coefficient increased with increasing temperature and air velocity (Wang et al., 2024). Metwally et al. (2024) carried out drying of three different varieties of dates (Sakkoti, Malkabii, and Gondaila) in two solar drying systems (automated solar dryer and open-air dryer) to study their drying coefficients. Compared to open air drying, the drying coefficient values of dates increased as the drying air temperature increased in the automated solar dryer (Metwally et al., 2024). Mbegbu et al. (2024) studied the effect of air temperature on the drying properties of bushbuck leaves at a temperature of 30 to 70 °C. They observed that the drying coefficient of bushbuck (Gongronema latifolium) leaves was temperature dependent, increasing as the temperature increased (Mbegbu et al., 2024). Moreover, it can be seen from **Table 1** that at almost all air temperatures, the reduction of the thickness of tomato slices led to an increase in the values of their drying coefficients. This was due to a short distance of the water diffusion path in tomatoes and subsequently led to a faster evaporation of water moisture from the surface of these wet samples. This observation on the effect of thickness is generally consistent with studies of the influence of the thickness of wet products during their drying in the literature such as apple slices (Demiray et al., 2023; Paul and Martynenko, 2022); turmeric slices (Abioye et al., 2021) and crabapple slices (Jiang et al., 2022). Paul and Martynenko (2022) determined the drying coefficient in the period of decreasing drying rate during electrohydrodynamic drying of apple slices. They found that higher drying coefficient values indicated a faster drying process. In their experiments, the drying coefficient values decreased significantly with increasing sample thickness, which could be explained by the exponential theory used to describe thin-layer drying (Paul and Martynenko, 2022).

In addition, 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 slice samples and as shown in the results in **Table 1**, the lag 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). **Table 1** shows that increasing the drying air temperature and decreasing the tomato slice thickness decreased the G values. This trend may imply that at high drying air temperature and small slice thickness, moisture evaporation from the samples was less retarded at the beginning of the process and the drying period with decreasing rate started from this beginning of the process. However, at low air temperature and larger tomato slice thickness, moisture evaporation was more retarded by the heating period of the wet samples, leading to a relatively long lag period. A similar observation was made by Demiray et al. (2023) for the drying of apple slices (Demiray et al., 2023), by Compaoré et al. (2022) for the drying of onion slices (Compaoré et al., 2022) and by Liu et al. (2013) for the convection drying of eggplant slices (Liu et al., 2013). In their context, Demiray et al. (2023) could say that the lag factor values resulted in decreased drying times with increasing drying temperature and decreasing slice thickness of apple samples. The reason for this is believed to be that apple slices dry faster at high temperatures and low thickness due to the high evaporation rate and reduced internal resistances critical to water transfer (Demiray et al., 2023).

***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

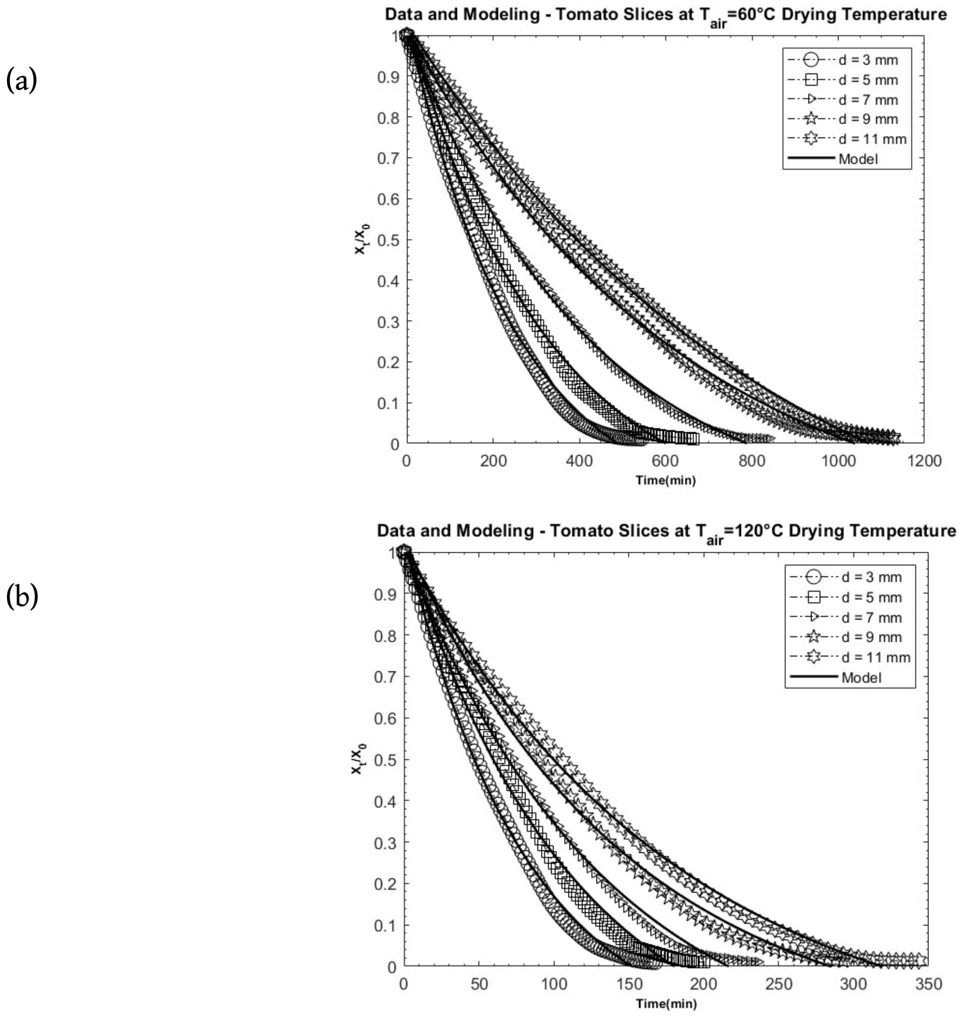

***Figure 1**: Experimental and predicted average moisture ratio of tomato slices at (a) 60°C air temperature and (b) 120°C air temperature for 3-11 mm thick samples.*

Influence of temperature and thickness on mass transfer Biot numbers (Bi_m)

The mass Biot number (Bi_m) is an important dimensionless parameter in the drying of common foods such as sweet potato and tomato. It explains the relationship between the diffusion resistance of internal moisture inside tomato samples 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 60–120 °C and sample thicknesses of 3–11 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 (Hai et al., 2022). They indicate the presence of external and internal resistances to moisture diffusion of tomato slices. The Bi_m values obtained for tomato slices were closer to 0.1, indicating that the effect of internal resistance on mass transfer was comparatively higher than that of external resistance. The results in **Table 2** showed that the Bi_m values were influenced by the drying air temperature and the thicknesses of tomato samples. It was observed that the Bi_m values decreased with the increase in drying air temperature for all the thicknesses of tomato samples. As the thicknesses of tomato slices increased, the Bi_m values also increased irrespective of the drying air temperature of the samples. This was due to increased internal resistance in these slices as the thicknesses of the samples increased. A similar trend of results under the drying conditions of air temperature and drying product thickness was reported for the characterization of pumpkin seed drying (Dhurve and Arora, 2023) and for the convective drying process of okra at various drying conditions (Agarry et al., 2021; Santos et al., 2021). Subsequently, the Bi_m values for tomato slices were used to obtain the μ_1 root for moisture transfer of the transcendental characteristic equation as shown in **Table 2**. These values ranged from 0.6359 to 0.7759 for our tomato slice drying conditions. These values decreased with increasing air temperature and decreasing tomato sample thickness. Similar trends were obtained in the case of drying of cocoyam (Ndukwu et al., 2017), chili peppers (Enahoro et al., 2022) and cornelian cherries (Polatoğlu and Aral 2022). Dhurve and Arora (2023) found that Bi_m values varied from 0.2910 to 0.6095 with the increase of air temperature from 40 to 60 °C during the drying of pumpkin seeds confirming the influence of temperature on this parameter (Dhurve and Arora, 2023).

***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}

Influence of temperature and thickness on moisture transfer parameters

Moisture diffusion is the rate of transfer of water molecules in wet food to different directions per unit time. This moisture diffusion of food during drying is a very complicated mechanism. Varietal theories, capillary flow, thermal and molecular diffusion, hydrodynamic flow, etc., have been proposed to explain the phenomenon of moisture diffusion in these foods. The effective moisture diffusivity (D_{eff}), which includes the interaction of these theories, is the most important parameter to control and improve the transport process since food drying is usually controlled by internal diffusion (Wang et al., 2024). Knowledge of moisture diffusivities for foods is very important because more complex mathematical models and correlations that can provide a deeper understanding of drying processes require data on D_{eff} (Dhurve and Arora, 2023). D_{eff} values for tomato slices, which refer to the ability of these slab samples to diffuse water from the inside to the outside, were calculated at air temperatures of 60–120 °C for thicknesses of 3–11 mm and the results are listed in **Table 2** and presented in **Figure 2**a. In this table, the D_{eff} for sliced tomatoes ranged from 3.90×10^{-10} to 1.06×10^{-8} m^2/s, for our drying conditions. These results are in the range of 10^{-12} to 10^{-8} m^2/s for food drying (Sun et al., 2024).

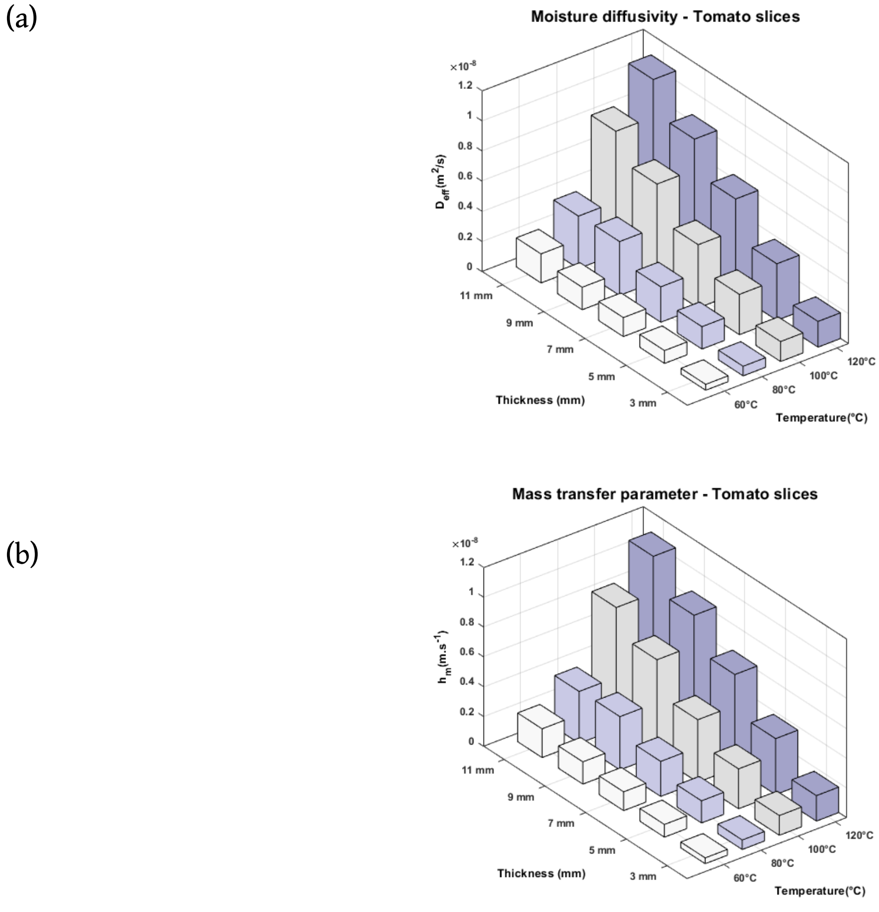

Figure 2: *Variation of effective moisture diffusivity (a) and mass transfer coefficient (b) of tomato slices versus air temperature for 3-11 mm sample thickness.*

In addition, the D_{eff} value depends on the drying temperature, variety and composition of the drying samples. For hot air drying of tomato slices, the D_{eff} values increased with increasing air temperature from 60 °C to 120 °C and increasing the thickness of tomato samples from 3 to 11 mm (**Figure 2**a and **Table 2**). This can be explained by the fact that the surface temperature of the sliced tomato samples increased when the drying temperature was increased, which enhanced the molecular motion and surface evaporation in the tomatoes. As a result, water molecules migrate outward (vaporize) with a greater need for thermal energy. This improves the ratio of moisture removal to convective drying time, which means that the drying samples lose moisture faster and the D_{eff} value has increased further. An increase in air temperature leads to a decrease in water viscosity and increases the activity of water molecules in the drying tomato samples. These phenomena facilitate the diffusion of water molecules into the different pores of the slices and, consequently, also increase the D_{eff} value (Tejeda-Miramontes et al., 2024). Similar air temperature trend results have been reported in the literature by researchers in hot air drying of wet products, including pumpkin seeds (Dhurve and Arora, 2023), watermelon seeds (Dhurve et al., 2022) and potatoes (Tepe, 2025). The D_{eff} value of cassava in the plexiglass drying chamber and plywood drying chamber was found to be 6.28×10^{-10} m²/s and 4.53×10^{-10} m²/s at the maximum temperatures of 55 °C and 52.5 °C, respectively, during solar drying of these cassava slices (Komolafe et al., 2024). During microwave drying of potato slices using different power levels (240 W, 400 W, 640 W) and different pretreatments (ethanol, hot water blanching, citric acid), the D_{eff} ranged from 3.29×10^{-9} to 1.10×10^{-8} m^2/s, increasing with higher power and application of pretreatment, while drying coefficients improved, reflecting improved moisture removal rates (Tepe, 2025). Elwakeel et al. (2024) determined by Crank diffusion approach the D_{eff} values for solar drying of tomatoes at different air velocities, collector movements and slice thicknesses. The data presented showed that the D_{eff} values increased with increasing tomato slice thickness for both designed systems, i.e., the follower collector motion system and the fixed collector motion system. Regarding the fixed collector motion system, while the minimum moisture diffusion was 2.73×10^{-10} m^2/s at air velocities of 2 m/s and slice thicknesses of 4 mm and 3.32×10^{-10} m^2/s at air velocities of 1 m/s and slice thicknesses of 4 mm of tomato, confirming the positive influence of the thickness on the D_{eff} of this drying product (Elwakeel et al., 2024). Moreover, the D_{eff} values of tarragon for drying in the sun, greenhouse solar and shade were reported as 10.64×10^{-7}, 2.12×10^{-7} and 1.34×10^{-7} respectively. These D_{eff} values significantly increased with higher temperatures. The increase in temperature enhanced molecular movement and the surface tension of water, resulting in a higher D_{eff} in the tarragon (Noshad et al., 2025).

Moisture transfer between the interface of dried food and hot air is an important mass phenomenon and is described by a convective moisture 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 for tomato slices was 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**). The h_m in the boundary layer at the surface of tomato slices depends on the airflow properties and drying conditions of the drying. For sliced tomato samples, h_m values increased with increasing air temperature and decreasing slice thickness, as shown in **Table 2** and **Figure 2**b. In fact, as shown in the results, when the air temperature increased from 60 °C to 120 °C for a sample thickness of 3 mm, h_m values increased from 2.98×10^{-7} to 2.03×10^{-6} m/s. On the contrary, for an air temperature of 120 °C, when the sample thickness increased from 3 to 11 mm, these values varied from 2.03×10^{-6} to 3.36×10^{-6} m/s. This variation in h_m values can be explained by a higher diffusivity, which increases the moisture transfer rate from the interior to the surface of the tomato slices during drying. Subsequently, this increases the moisture concentration gradient between the tomato surface and the surrounding air, thereby increasing the rate of water vapor absorption by the air. In addition, heat and mass transfer also occur in tomatoes due to the circulation of air surrounding the samples that increases the convection mechanism, resulting in a higher h_m (Rajoriya et al., 2021). Moreover, the moisture transfer rate from the surface of sliced samples depends on the thickness of the thermal and concentration boundary layers along the surfaces of these samples. The thickness of the thermal and concentration boundary layers arises from the temperature and concentration difference between the surfaces of the tomato samples and the forced-flow drying air. Higher drying temperatures increase the evaporative capacity of the free-flow drying air and lead to higher mass transfer rates (Beigi, 2017). In the literature, similar reports on the influence of air and sample parameters on hm have been presented for pumpkin seeds (Dhurve and Arora, 2023), okra (Agarry et al., 2021) and jackfruit (Tuly et al., 2023). Meanwhile, the h_m of pumpkin seeds improved from 3.321×10^{-8} to 8.656×10^{-8} m/s, with the increase of air temperature from 40 to 60 °C and air velocity by 1.5 m/s (Dhurve and Arora, 2023). Then, the h_m values for cassava slices dried at maximum air temperatures of 55 °C and 52.5 °C were 1.70×10^{-6} and 1.67×10^{-6} m/s, respectively, under natural convective solar drying (Komolafe et al., 2024). Finally, the h_m for the three varieties of taro slices ranged from 1.01044×10^{-6} to 3.44876×10^{-6} m/s for increasing drying temperatures from 50 to 70 °C. All three varieties showed an increasing trend in mass transfer with increasing air temperatures. Variations in food material mass transfer also depended on the composition matrix, size, shape, and initial moisture content (Ndukwu et al., 2017).

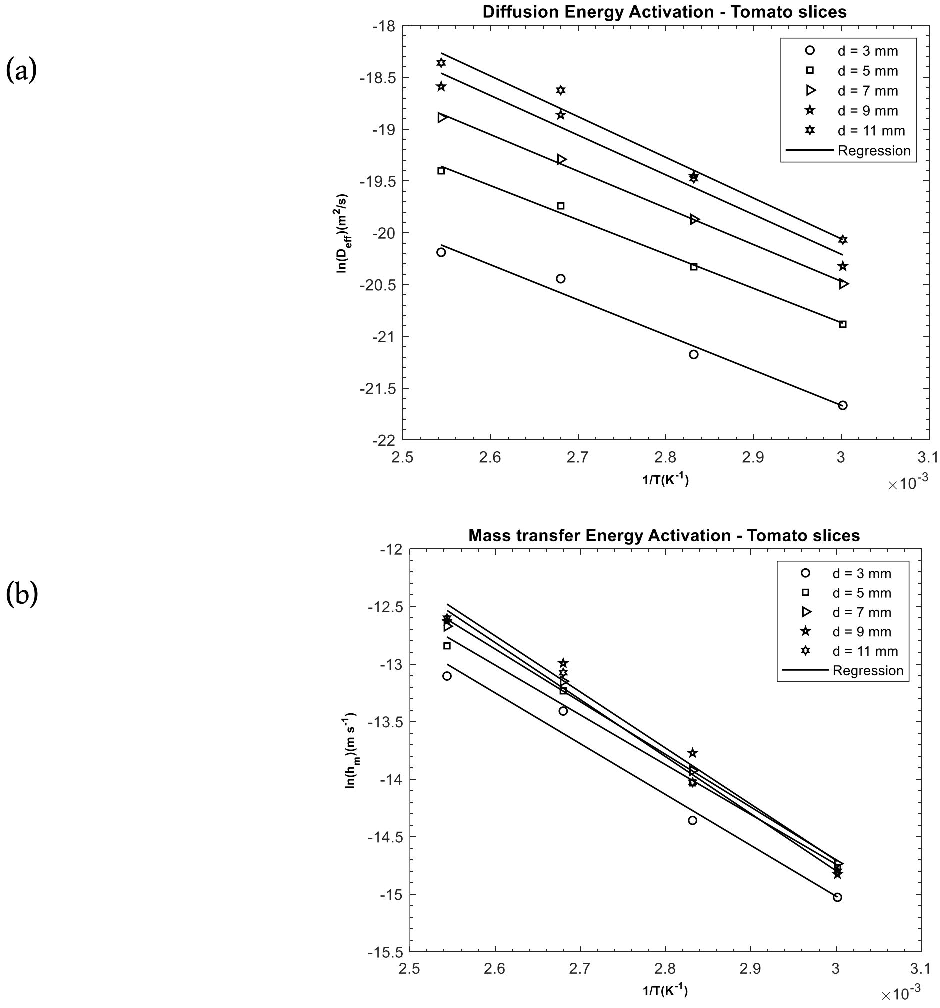

Figure 3: *Representation by the Arrhenius-type equation for drying tomato slices: (a) of moisture diffusivity; (b) convective mass transfer coefficient.*

Influence of thickness on activation energy

For engineering applications, it is useful to obtain Arrhenius functions that describe the effect of air temperature on Deff and hm. The Arrhenius functions expressing the evolution of Deff and hm for tomato slices as a function of air temperature are evaluated by least-squares fitting of the drying data in Table 2 as ln (Deff) and ln(hm) to the inverse of the absolute air temperature, using equations (15) and (17) respectively. The natural logarithm of Deff and hm for tomato slices 3–11 mm thick was plotted against the inverse of the absolute air temperature as shown in Figure 3. In this figure, the values of the activation energy for moisture diffusion (Ea-d) and for convective mass transfer (Ea-c) are obtained from the different slopes of the curves. The Ea-d value reflects the sensitivity of Deff 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 $E_{a\text{-}d}$ 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 $E_{a\text{-}c}$ 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 $E_{a\text{-}d}$ values are in the range of 12.70–110.00 kJ/mol for most agricultural products (Yamchi et al., 2024). The Ea-d values in the present study were comparatively close to the activation energies of other works, namely the value of 34.90 kJ/mol for convection drying of raspberry pomace at 50-90 °C (Tejeda-Miramontes et al., 2024). Our Ea-d values were relatively increasing with increasing tomato slice thickness, suggesting a higher resistance to moisture diffusion in tomato slices due to the increase in water diffusion distance in tomato samples. This similar trend was found by other previous studies including drying of ripe and unripe bitter melon slices (Yamchi et al., 2024) and infrared drying of whole larvae at air temperatures of 50–70 °C (Butwong et al., 2025). The Ea-d values of black soldier fly larvae increased from 56.88 347 kJ/mol at an air velocity of 1.0 m/s to 115.41 kJ/mol at an air velocity of 2.0 m/s during infrared drying for sustainable cricket feed production, suggesting that more energy was required than necessary in cases of drying larvae at high air velocity (Butwong et al., 2025). Sun et al. (2024) obtained that during forced convection drying of Hami melon (Cantaloupe) slices at temperatures ranging from 60 to 90 °C, the Ea-d values of melon slices with a thickness of 3 mm and 5 mm were 30.13 and 43.75 kJ/mol, respectively. The increase in activation energy was due to the initial increase in the energy required to remove one mole of water from the product during the drying process (Sun et al., 2024). However, Yamchi et al. (2024) found that by increasing the ultrasonic pretreatment time of the bitter melon during infrared drying, the Ea-d values for initiating diffusion decreased from 37.49 to 36.74 kJ/mol. Indeed, with the increase of ultrasonic pretreatment time, the moisture permeability of bitter melon increased and the energy required to start the penetration of the internal parts would be less (Yamchi et al., 2024). Moreover, our Ea-c values which are respectively 36.717 kJ mol-1, 35.977 kJ mol-1, 38.047 kJ mol-1, 40.550 kJ mol-1 and 41.206 kJ mol-1 for tomato thicknesses of 3 mm, 5 mm, 7 mm, 9 mm and 11 mm, increase with the increase in the thickness of the tomato slices (**Table 3**). These trends are similar to the variations of Ea-c in the literature including convective dehydration of Jatropha seeds (Agbede et al., 2024), drying of thistle flower (Guiné et al., 2019) and drying of kiwifruit slices (Mohammadi et al., 2019). Guine et al. (2017) obtained Ea-c values for kiwifruit and eggplant which were 50.842 and 48.491 kJ/mol, respectively. This difference could be attributed to the chemical composition of the drying products (Guine et al., 2017).

***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

Conclusion

The influence of drying parameters such as air temperature and sample thickness on the mass and moisture transport parameters of tomato slices was investigated at 60°C, 80°C,100°c and 120°C air temperatures for 3-, 5-, 7- and 11-mm thickness samples. Using the experimental data, the aim of this study is to determine the influence of air temperature and sample thickness on the mass and moisture transport parameters such as lag factor, drying constants, moisture diffusivities, and moisture transfer coefficient for tomato slices subjected to convective drying. For drying kinetics, the drying curve 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. Concerning the influence results, the drying coefficient of tomatoes increased with increasing drying temperature whatever the employed sample thickness. at almost all air temperatures, reducing the tomato thickness caused the drying coefficient to increase. The increase in drying air temperature and decrease in tomato thickness decreased the lag factor values. The mass Biot number values decrease with increase in the drying air temperature for all sample thickness. When tomato thickness increases, the mass Biot number values increased also whatever drying air temperature of samples. For hot air drying of sliced tomatoes, moisture diffusivity values increased with increased air temperature from 60°C to 120°C and increased sample thickness from 2 cm to 11 mm. The activation energy values for moisture diffusion and convective mass transfer were decreased with increasing samples thickness for all drying conditions applied. The results of this study are useful to serve input data in simulation of convective oven dryer and to optimize drying process parameters for commercial scale production of dried tomato.

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List of Symbols

d	Diameter of the product (m)
d.b.	dry basis
D_0	Constant of Arrhenius type (m^2 s^{-1})
D_{eff}	Effective moisture diffusivity (m^2 s^{-1})
F_0	Fourier number (-)
E_a	Activation energy (J mol^{-1})
$m(t)$	mass of wet product (kg)
min	minute (min)
m_s	Dry mass (kg)
MR	Moisture ratio (-)
n	Positive integer (-)
r	Radius (m)
R	Universal gas constant = 8314.46 J mol^{-1} K^{-1}
R^2	Coefficient of determination (-)
RMSE	Root-Mean-Square error (-)
SSE	Sum of squared error (-)
t	Tim (s)
T	Air Temperature (°C or K)
X_0	Initial mean moisture content ($kg_{water}/kg_{dry\ mass}$)
X_e	Equilibrium moisture content ($kg_{water}/kg_{dry\ mass}$)
$X(t)$	Moisture content ($kg_{water}/kg_{dry\ mass}$)
$\chi 2$	Chi-square reduced (-)