Experimental and Mathematical Investigations of Apple Slices Convective Drying

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Abstract: The aim of this work was to determine sorption isotherms and thin layer convective drying behavior of apple slices and to compare the experimental and calculated results by using models available in the literature. The sorption isotherm was determined at four temperature levels 40, 50, 60 and 70 °C and at water activity ranging from 0.058 to 0.89, using the static gravimetric method. A non-linear regression procedure was used to fit experimental sorption isotherms and drying curves with most used empirical mathematical models available in literature. It was found that the Peleg model suitably represent the sorption experimental data in the mentioned investigated ranges of temperature and water activities. The Midilli et al. model satisfactorily described the thin layer drying behavior of apple slices. The drying characteristic curve and the thin layer drying rate expression of apple slices have been established from experimental convective drying kinetics. The values of the diffusivity coefficients at each condition were obtained using Fick's second law of diffusion. They varied from 8.51×10^{-8} to 3.28×10^{-7} m²/s in the temperature range of 40-70 °C and in the relative humidity range of 20%-40%. The activation energies for moisture diffusion were calculated to vary from 26.72 to 35.83 kJ/mol.

Key words: Convective drying, sorption isotherm, isosteric heat, apple, empirical modeling, effective diffusivity, activation energy.

1. Introduction

In order to improve the quality of the dried product, industrial dryers should be used in place of traditional sun drying. Industrial dryers provide uniform dried product, hygiene and also the process is more rapid [1]. An important factor in the loss of quality of dried foods during storage is the water activity (a_w) which influences the biochemical reactions and stability of dried products. Some of these reactions are lipid oxidation, caking, agglomeration and degradation of vitamins and lycopene [2, 3]. Knowledge of sorption isotherm and drying behavior are of great importance in food dehydration, especially in the quantitative approach to the prediction of the shelf life of dried foods [4]. Equations for modelling water sorption isotherms are of special interest for many aspects of

food preservation by dehydration, including evaluation of the thermodynamic functions of the water sorbet in foods. Knowledge of the thermodynamic properties associated with sorption behavior of water in foods is important to dehydration in several respects, especially in the design and optimization of unit operation, and further help the understanding and interpretation of sorption mechanisms and food-water interactions.

Several thin layer equations available in the literature for explaining drying behavior and sorption isotherms of agricultural products have been used by Diamante and Munro for sweet potato slices [5], Toujani et al. for silverside fish [6], Madamba et al. for garlic slices [7], Midilli for pistachio [8], Yaldız et al. for grape [9], Basunia and Abe for rough rice [10], Panchariya et al. for black tea [11], Dandamrongrak et al. for banana [12], Lahsasni et al. for prickly pear peel [13], Kalpana et al. for betel leaf

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[14], and Guran and Kamil for hawthorn fruits [15]. The present study were, therefore, undertaken to investigate the sorption isotherms and the thin layer drying characteristics of apple “Golden delicious” slices in a convective dryer and to fit the experimental data to mathematical models available in the literature. In addition, the effective diffusivities and activation energy in the convective drying process of apple slices are calculated.

2. Materials and Methods

2.1 Materials

Fresh apple “Golden delicious” was purchased from local market. Upon arrival to the laboratory and before drying, apples were washed hand, peeled and cut into rectangle-shaped slices (dimensions in mm: $40 \times 10 \times 10$). The slices were blanched in water at 90°C during 5 min to prevent enzymatic browning and immediately cooled in water at 15°C during few minutes to remove excess heat. The water remaining at the surface was removed with a filter paper. In order to characterize the fresh apple, analyses were realized according to the methods of Association of Official Analytical Chemists [16]. Moisture content was measured using the gravimetric method in an oven at 70°C up to constant weight (≈ 24 h). The mean water content of the fresh product is about $86 \pm 3\%$ (dry basis).

2.2 Methods

2.2.1 Desorption Isotherms

(1) Experimental procedure

A static gravimetric method has been used for the determination of the apple sorption isotherms at four temperatures $40, 50, 60$ and 70°C . The salts are dissolved in distilled water at a higher temperature than the working one; a saturated solution is obtained when the liquid phase is in equilibrium with the salt crystals [17]. The prepared solution is then cooled to the working temperatures. To avoid the formation of a concentration gradient in the liquid phase, the salt solution is agitated continuously. Nine saturated salt

solutions were prepared corresponding to a range of water activities of 0.058 – 0.891 (Table 1). These solutions are prepared in hermetic jars and are maintained in a drying room regulated in desired temperature. The sample is suspended in the jar, above salts. The required equilibration time was 15 – 20 days based on the change in weight expressed on a dry basis, which did not exceed 0.1% . The weight was $< 1 \text{ mg g}^{-1}$ dry solids for three consecutive weightings at intervals of minimum 5 days [20]. The equilibrium moisture content is calculated by:

$$X_e = \frac{M_f - M_d}{M_d} \quad (1)$$

In this expression, X_e is the equilibrium moisture content (kg water / kg dry matter), M_f is the final weight (kg), M_d is the dry weight solid (kg).

(2) Modelling of sorption isotherms curves

Various empirical correlations exist in the scientific literature to model the desorption curves such as BET, Oswin, GAB, Modified Halsey and Peleg. These models are described in Table 2. The model parameters were obtained from experimental data by nonlinear regression analysis using a least-squares Levenberg Maquardt algorithm implemented in the ORIGIN 6.0 program. The determination coefficient (R^2) and the reduced chi-square (χ^2) were retained to evaluate the goodness fit of the models. The lower χ^2 and the higher R^2 values are chosen as criteria for goodness of fit. These parameters have been given by Eqs (2) and (3) [26, 27]:

$$R^2 = 1 - \frac{\sum_{i=1}^n (X_{e,i,\text{exp}} - X_{e,i,\text{pre}})^2}{\sum_{i=1}^n (\bar{X}_e - X_{e,i,\text{pre}})^2} \quad (2)$$

$$\chi^2 = \frac{\sum_{i=1}^n (X_{e,i,\text{exp}} - X_{e,i,\text{pre}})^2}{N - z} \quad (3)$$

where $X_{e,i,\text{exp}}$ is the i th experimental equilibrium moisture, $X_{e,i,\text{pre}}$ is the i th predicted equilibrium moisture, N is the number of observations, z is the number of constants in the drying model and $\bar{X}_e$ is the average value of experimental equilibrium moisture was calculated by using this relation:

Table 1 Selected saturated salt solutions and corresponding water activity [18, 19].

Solutions	Temperature (°C)			
	40	50	60	70
NaOH	0.0598	0.0583	0.0648	0.0698
KOH	0.0626	0.0572	0.0549	0.0532
MgCl ₂	0.3159	0.3054	0.2926	0.2777
K ₂ CO ₃	0.4230	0.4091	0.3921	0.3737
NaBr	0.5317	0.5083	-	-
NaNO ₃	0.7100	0.6904	0.6735	0.6001
NaCl	0.7501	0.7484	0.7028	0.7455
KCL	0.8232	0.8120	0.8025	0.7949
BaCl ₂	0.8910	0.8823	0.8728	0.8625

Table 2 The models applied to the experimental sorption data of apple.

Model name	Model equation	References
BET	$X_{eq} = \frac{A.B.a_w}{(1-a_w)(1+(B-1).a_w)}$	[21]
Oswin	$X_{eq} = A\left(\frac{a_w}{1-a_w}\right)^B$	[22]
GAB	$X_{eq} = \frac{A.B.K.a_w}{(1-K.a_w)(1+(B-1)K.a_w)}$	[23]
Modified Halsey	$X_{eq} = A\left(-\frac{B}{Ln a_w}\right)^{\frac{1}{C}}$	[24]
Peleg	$X_{eq} = A(a_w)^B + C.(a_w)^D$	[25]

$$\overline{Xe} = \frac{1}{N} \sum_{i=1}^N Xe_{i,exp} \quad (4)$$

(3) Estimation of sorption isosteric heat

The net isosteric heat (q_{st}) is defined as the total heat of sorption of water from the material minus the heat of water vaporisation at the same temperature. Conventionally, q_{st} is a positive quantity when heat is evolved during adsorption, and negative when heat is absorbed during desorption. The isosteric heat of sorption plays an important role in the determination of the time and the energy requirements for drying [28]. This parameter can be estimated by using the Clausius-Clapeyron equation, at fixed moisture contents [29, 30], as shown in Eq. 5:

$$\ln(a_w) = -\left(\frac{q_{st}}{R}\right)\left(\frac{1}{T}\right) + K \quad (5)$$

where q_{st} is the net isosteric heat of sorption (kJ/mol),

a_w is the water activity (dimensionless), T is the absolute temperature (K), R is the universal gas constant (kJ/mol K) and K is a constant.

In an attempt to describe the relationship between the net isosteric heat of sorption and the moisture content, Tsami et al. proposed an empirical exponential correlation [30], which can be written as Eq. 6:

$$q_{st} = q_0 \cdot \exp\left(\frac{-X_e}{X_0}\right) \quad (6)$$

In this expression, X_e is the equilibrium moisture content (kg water/kg dry matter), q_0 is the net isosteric heat of sorption of the first molecule of water in the food (kJ/mol), and X_0 is a characteristic moisture content of the food material (kg water/kg dry matter).

2.2.2 Drying Experiments

(1) Experimental set-up

The unit of drying used is a climatic blower available in Energetic and the Mass and Thermo Transfers Laboratory of University of Tunis (Tunisia). A convective dryer by the hot air was used for drying, which could be regulated to any desired drying air temperature, relative humidity and velocity of drying air with high accuracy. Principal elements of this process are a centrifugal blower to aspire the ambient air, an electrical resistance air heating section ensuring the rise in the temperature of the air, heating control unit, a steam air moistening section, measurement sensors and a drying chamber. A balance of high precision located at the lower part of the dryer. Temperature, air velocity and relative humidity inside the vein are adjusted and controlled using an automatic system of regulation. The measurement sensors, the data recording and controlling system coupled with a computer. The hot-air orientation on the samples was vertical. The advantage of this type of flow is to offer optimum conditions for contact air-product and a coefficient of significant heat transfer (Fig. 1).

During drying in the convective dryer, the weight losses of the samples were measured at 10 min

Fig. 1 Experimental laboratory dryer.

1: air flow regulator; 2: centrifugal fan; 3: electric resistance; 4: steam injection for air humidity control; 5: air steam direction; 6: apple slices; 7: perforated tray; 8: thermocouple; 9: data logger; 10: computer; 11: electronic balance.

intervals. The drying tests were terminated when the mass of the samples reached a constant value. The air drying conditions are: the temperature and the relative humidity of drying air range from 40 to 70 °C and 20% to 40% respectively. All experiments were conducted for an air velocity of 1.5 m/s. These experiments were replicated thrice to obtain a reasonable average.

(2) Characteristic drying curves

The characteristic drying curve method [31] was chosen to describe the falling rate period of the conditions, by a single normalized drying rate curve. This curve type can be used to generalize data for drying kinetics of thin layer of apple slices in a convective dryer. Kouhila et al. [17], Bellegha et al. [32], Timoumi et al. [33] based on the Van Meel transformation [34], have used simply the initial moisture content (X_0) instead of the critical moisture content (X_{cr}) and the initial drying rate $(dX/dt)_0$ instead of the drying rate relative to the constant rate period $(dX/dt)_l$, Eqs. 7 and 8.

$$X \rightarrow XR = \frac{X - X_{eq}}{X_0 - X_{eq}} \quad (7)$$

$$-\left(\frac{dX}{dt}\right) \rightarrow f = \frac{-\left(\frac{dX}{dt}\right)}{-\left(\frac{dX}{dt}\right)_0} \quad (8)$$

where X_0 : initial moisture content (kg water / kg dry matter), X_e : equilibrium moisture content (kg water / kg dry matter), XR : moisture ratio, $(dX/dt)_0$: initial drying rate (kg water / kg dry matter), f : dimensionless drying rate.

(3) Empirical drying equations

Mathematical modeling using thin layer drying models has been studied in drying of fruits, vegetables, seafood and other agriculture or crop products [9, 35-38]. The models fall into three categories namely the theoretical, semi-theoretical and empirical. Semi-theoretical models offer a compromise between theory and ease of application [39]. For the present study this approach has been taken. Thus eleven semi-empirical models were applied to describe the convection drying kinetics of thin layer of apple slices Table 3 summarizes the mentioned thin layer drying models used in the data fit analysis of this work.

The regression was performed by the Levenberg—Marquardt procedure using Origin 6.0 program. The coefficient of determination (R^2) was one of the primary criteria for selecting the best model to describe thin-layer drying curves of apple slices. In addition to this coefficient, the reduced chi-square (χ^2) to evaluate the goodness of fit of the models. The lower χ^2 values and the higher R^2 values, which were chosen as the criteria for goodness of fit. These parameters can be described in Eqs. (9) and (10) [26, 27]:

$$R^2 = 1 - \frac{\sum_{i=1}^n (XR_{i,exp} - XR_{i,pre})^2}{\sum_{i=1}^n (\overline{XR}_{i,exp} - XR_{i,pre})^2} \quad (9)$$

$$\chi^2 = \frac{\sum_{i=1}^n (XR_{i,exp} - XR_{i,pre})^2}{N - z} \quad (10)$$

Where $XR_{i,exp}$ is the i th experimental moisture ratio, $XR_{i,pre}$ is the i th predicted moisture ratio, N is the number of observations, z is the number of constants in the drying model and $\overline{XR}_{i,exp}$ is the average value of experimental moisture ratio was calculated by using this relation:

$$\overline{XR}_{i,exp} = \frac{1}{N} \sum_{i=1}^N XR_{i,exp} \quad (11)$$

Table 3 Mathematical models applied to fit the apple slices thin layer drying curves.

Name of the model	Equations	References
Lewis	$XR = \exp(-k.t)$	[40]
Page	$XR = \exp(-k.t^n)$	[41]
Modified Page	$XR = \exp(-k.t)^n$	[42]
Henderson and Pabis	$XR = a.\exp(-k.t)$	[43]
Logarithmic	$XR = a.\exp(-k.t) + c$	[27]
Two-term model	$XR = a.\exp(-k_0.t) + b.\exp(-k_1.t)$	[44]
Approximation of diffusion	$XR = a.\exp(-k.t) + (1-a).\exp(-k.a.t)$	[9]
Wang and Singh	$XR = 1 + a.t + b.t^2$	[45]
Simplified Fick's diffusion	$XR = a.\exp(c.(t/L^2))$	[46]
Modified Page equation-II	$XR = a.\exp(c.(t/L^2)^n)$	[46]
Midilli et al.	$XR = a.\exp(-k.t^n) + b.t$	[38]

3. Results and Discussion

3.1 Desorption Isotherms and Modelling

In all cases, the R^2 and χ^2 values for models changed from 0.98282 to 0.99898, 0.00002 to 0.00033, respectively. Therefore, the Peleg model was the best descriptive model as shown in Table 4, suggested by the highest average R^2 value which equals to 0.99898 and the lowest average χ^2 value which equals to 0.00002. Accordingly, the Peleg model was selected as suitable model to represent the sorption isotherms behavior of apple slices in the water activity range of 0.05-0.9 and the temperature range of 40-70 °C. Apple hygroscopic equilibrium moisture is reached at the end of 15 days. As shown in the sorption curves (Fig. 2), a significant temperature effect was observed on desorption isotherms. At constant temperature, the equilibrium moisture content increased with increasing water activity and at constant water activity, the equilibrium moisture content increases with decreasing temperature. In general, both temperature and water activity have significant effects on experimental equilibrium moisture content values. Similar trends have been observed in several other studies concerning other foodstuffs [17, 47].

3.2 Isosteric Heat of Desorption

The net isosteric heat can be estimated by plotting the sorption isotherms as $\ln(a_w)$ versus. The inverse of

temperature ($1/T$) for selected material moisture content, and determining the slope which is $(-q_{st}/R)$, hence q_{st} is determined. The results are given in Fig. 3.

As shown in Fig. 4, the net isosteric heat of sorption was high at lower moisture contents and then decreased reaching a constant value at high moisture content (above moisture content around 0.15 kg kg⁻¹ db). At low moisture content, the net isosteric heat of sorption was high, indicating the highest binding energy for water removal. The decrease in the heat of sorption indicates that the water-solid interactions are weakened at high moisture content levels. The same results were reported by Toujani et al. [6] for silverside fish, Nourhene et al. [48] for olive leaves, Medeni and Fahrettin [28] in the case of pistachio.

From Tsami's equation, the q_0 and X_0 values for desorption data were 35.3213 kJ mol⁻¹ and 0.1779 kg kg⁻¹ db respectively, with an R^2 equal to 0.993. Marcel et al. obtained for the *Gnetum africanum* q_0 value around of 68.523 (kJ mol⁻¹) and X_0 value of 0.063 (kg kg⁻¹db) [49]. Kiranoudis et al. obtained for fruits and some plants, a q_0 value varying between 40 and 115 kJ mol⁻¹ and X_0 varying from 0.08 to 21 (kg kg⁻¹db) [50].

3.3 Drying Curves

The drying curves obtained were fitted with 11 different moisture ratio models (Table 4). For results of moisture ratio obtained in experiments for thin-layer

Table 4 Results of the fitting statistics of various models at different drying temperatures.

Model name	T (°C)	Parameters				R ²	χ^2
BET	40	A = 1.1105	B = 0.1955			0.99130	0.00025
	50	A = 0.9566	B = 0.1864			0.98296	0.00029
	60	A = 0.2737	B = 0.3682			0.99618	0.00005
	70	A = 0.1448	B = 0.4940			0.99722	0.00002
Oswin	40	A = 0.1285	B = 0.6442			0.99505	0.00014
	50	A = 0.1035	B = 0.6409			0.98753	0.00021
	60	A = 0.0673	B = 0.7906			0.99741	0.00003
	70	A = 0.0527	B = 0.8511			0.99783	0.00002
GAB	40	A = 1.1641	B = 0.1876	K = 1.0029		0.99131	0.00028
	50	A = 0.2550	B = 0.5874	K = 0.8891		0.98778	0.00024
	60	A = 0.0984	B = 0.8059	K = 0.9406		0.99779	0.00003
	70	A = 0.0885	B = 0.7165	K = 0.9721		0.99764	0.00002
Modified Halsey	40	A = 0.2708	B = 0.2605	C = 1.2918		0.99729	0.00009
	50	A = 0.2425	B = 0.2262	C = 1.2848		0.98282	0.00033
	60	A = 0.2104	B = 0.2076	C = 1.0594		0.99369	0.00009
	70	A = 0.1940	B = 0.1938	C = 0.9798		0.99626	0.00004
Peleg	40	A = 0.1502	B = 0.4738	C = 0.7090	D = 6.0073	0.99700	0.00009
	50	A = 0.0771	B = 0.3366	C = 0.4902	D = 4.1300	0.99531	0.00011
	60	A = 0.4882	B = 4.9157	C = 0.0567	D = 0.5214	0.99898	0.00002
	70	A = 0.0603	B = 0.6816	C = 0.4509	D = 5.7064	0.99759	0.00003

Fig. 2 Experimental and predicted (Peleg) sorption isotherms of apple. **Fig. 3** Clausius—Clapeyron-type relationship between water activities and temperature for apple. **Fig. 4** Experimental and estimated net isosteric heat for different equilibrium moisture contents.

drying of apple slices carried out at 40-70 °C temperature and 20%-40% relative humidity and flowing at a constant speed of 2 m/s, as can be observed a constant rate-drying period was not detected in drying curves. The curves typically demonstrated smooth diffusion controlled drying behavior under all run conditions. Moreover, an important influence of air drying temperature on drying rate could be observed in these curves.

Drying rate increased with the increase of air-drying temperature and the highest values of drying rate were obtained during the experiment at

70 °C of the drying air and the relative humidity are a small effect of drying rate. The results were generally in agreement with some literature studies on drying of various food products [4, 35, 51].

3.4 Characteristic Drying Curve

Marquardt-Levenberg nonlinear optimization method, using the computer program Origin 6.0, was used to find the best equation for apple slices characteristic drying curve. According to our results, the characteristic fitting of the drying curves drying curve of thin layer of apple slices is depicted in Fig. 5. The best fitting of this curve is carried out by a polynomial equation of degree 3:

$$f = 0.9622XR^3 - 1.2354XR^2 + 1.2659XR - 0.0583 \quad (12)$$

The criterion used to evaluate goodness of fit was the correlation coefficient ($R^2 = 0.99$). This function (Eq. 12) characterizes the convective drying process of apple slices dried in single layer in a temperature ranging from 40 to 70 °C, a relative humidity varying from 20% to 40%, at an air velocity of 2 m s⁻¹.

3.5 Fitting of the Drying Curves

The results of statistical analysis on the eleven drying models relating the drying time and moisture ratio with the experimental condition for drying temperatures of 40, 50, 60 and 70 °C and relative humidity of 20%, 30% and 40% (Table 5).

All the models give consistently high coefficient of determination (R^2) values in the range 0.97259-0.99981. This indicates that all the models could satisfactorily describe the thin layer air-drying of apple slices. The results show that the highest values of R^2 and the lowest values of χ^2 can be obtained with the Midilli et al. drying model.

The model coefficients and exponent of selected model, obtained after these regressions are given in Table 6. According to the results of thin layer drying of apple slices, Midilli et al. model could be used to predict the moisture ratio of the product at any time of drying process (Figs. 6-8).

Fig. 5 Drying characteristic curve of apple obtained for different drying experiments.

3.6 Calculation of Effective Diffusivity and Activation Energy

The thin layer drying of apple slices occurs in the falling rate period only and liquid diffusion controls the process. Fick's second law can be used to describe the thin layer drying of apple slices. General series solution of Fick's second law in Cartesian coordinates is given below (Eq. 13).

$$XR = \frac{X - X_e}{X_0 - X_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{L^2}\right) \quad (13)$$

where D_{eff} is the effective diffusivity and L is the thickness of thin layer of apple slices.

This equation was applied assuming one-dimensional moisture movement without volume change; a constant diffusivity, uniform moisture distribution and negligible external resistance [51].

The Eq. (13) can be simplified by taking the first term Eq. (14):

$$XR = \frac{8}{\pi^2} \cdot \exp\left(-\frac{\pi^2 D_{eff} t}{L^2}\right) \quad (14)$$

The effective diffusivity was obtained when $\ln(XR)$ was plotted versus t

$$\ln XR = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff} t}{L^2} \quad (15)$$

$$\text{slope} = -\frac{\pi^2 D_{eff}}{L^2} \quad (16)$$

Table 5 Statistical results obtained from different thin-layer drying models.

Model name	T (°C)	RH = 20%		RH = 30%		RH = 40%	
		R ²	χ^2	R ²	χ^2	R ²	χ^2
Lewis	40	0.98153	0.00108	0.98939	0.00063	0.99162	0.00049
	50	0.97714	0.00132	0.99233	0.00045	0.99692	0.00019
	60	0.99637	0.00025	0.99021	0.00061	0.99674	0.00022
	70	0.9977	0.00018	0.99798	0.00016	0.99412	0.00047
Page	40	0.99494	0.0003	0.99894	0.00006	0.99962	0.00002
	50	0.99651	0.00021	0.99982	0.00001	0.99914	0.00005
	60	0.99821	0.00013	0.9985	0.0001	0.99814	0.00013
	70	0.99776	0.00018	0.99798	0.00016	0.99553	0.00036
Modified page	40	0.98153	0.0011	0.98939	0.00064	0.99162	0.0005
	50	0.97714	0.00135	0.99233	0.00046	0.99692	0.0002
	60	0.99637	0.00026	0.99021	0.00063	0.99674	0.00023
	70	0.9977	0.00019	0.99798	0.00016	0.99412	0.00048
Henderson and Pabis	40	0.99489	0.0003	0.99719	0.00017	0.99772	0.00013
	50	0.98976	0.00061	0.99723	0.00017	0.99895	0.00007
	60	0.99702	0.00021	0.99672	0.00021	0.9984	0.00011
	70	0.99773	0.00018	0.99809	0.00015	0.99426	0.00047
Logarithmic	40	0.99489	0.00031	0.99783	0.00013	0.99883	0.00007
	50	0.99228	0.00047	0.99886	0.00007	0.99908	0.00006
	60	0.99754	0.00018	0.99719	0.00019	0.99856	0.00017
	70	0.99893	0.00009	0.99899	0.00008	0.99919	0.00007
Two-term	40	0.99896	0.00006	0.99991	5.56×10^{-6}	0.99985	9.31×10^{-6}
	50	0.99822	0.00011	0.99986	8.80×10^{-6}	0.99964	0.00002
	60	0.99858	0.00011	0.99949	0.00003	0.99902	0.00007
	70	0.99773	0.0002	0.99816	0.00016	0.99426	0.0005
Approximation of diffusion	40	0.98157	0.0011	0.9895	0.00064	0.99176	0.00049
	50	0.97728	0.00134	0.99245	0.00046	0.99702	0.00019
	60	0.99641	0.00026	0.99032	0.00062	0.99682	0.00022
	70	0.99772	0.00019	0.99805	0.00016	0.99417	0.00048
Wang and Singh	40	0.93646	0.00378	0.95603	0.00266	0.97259	0.00162
	50	0.93817	0.00366	0.97905	0.00126	0.98582	0.00091
	60	0.98121	0.00135	0.96162	0.00247	0.97413	0.00179
	70	0.98475	0.00124	0.97025	0.00238	0.98575	0.00116
Simplified Fick's diffusion	40	0.99489	0.00031	0.99719	0.00017	0.99772	0.00014
	50	0.98976	0.00062	0.99723	0.00017	0.99895	0.00007
	60	0.99702	0.00022	0.99672	0.00022	0.9984	0.00011
	70	0.99773	0.00019	0.99809	0.00016	0.99426	0.00048
Modified page equation-II	40	0.99633	0.00023	0.99923	0.00005	0.99973	0.00002
	50	0.99653	0.00022	0.99983	0.00001	0.99931	0.00005
	60	0.99828	0.00013	0.99879	0.00008	0.99849	0.00011
	70	0.998	0.00018	0.9982	0.00016	0.99611	0.00034
Midilli et al.	40	0.9994	0.00004	0.99972	0.00002	0.99981	0.00001
	50	0.99736	0.00016	0.99988	7.54×10^{-6}	0.99934	0.00004
	60	0.9983	0.00013	0.9997	0.00002	0.99981	0.00001
	70	0.99926	0.00006	0.99915	0.00007	0.99971	0.00002

The effective diffusivity was calculated by Eq. (15), using slopes Eq. (16) derived from the linear regression of $\ln(XR)$ against time data shown in Figs. 9-11. Generally an effective diffusivity is used due to limited information on the mechanism of moisture movement during drying and complexity of the process. The effective diffusivity (D_{eff}) during thin layer drying of apple slices varied from 8.51×10^{-8} to

$3.28 \times 10^{-7} \text{ m}^2/\text{s}$ in the temperature range from 40 to 70 °C and in the relative humidity range from 20% to 40% (Table 7). The obtained values are in the suitable range for various products reported in the literature [52, 53]. The effective diffusivities increased with temperature as expected.

Effective diffusivity can be related with temperature by Arrhenius expression Eq. (17) [54].

Table 6 Values of statistical parameters for Midilli et al. model.

Midilli et al.	T (°C)	Parameters				R^2	χ^2
		a	k	b	n		
RH=20%	40	1.00051	0.01123	-0.00003	0.92943	0.99959	0.00003
	50	1.00051	0.02302	-0.00032	0.81647	0.99927	0.00006
	60	1.00051	0.00962	-0.00016	1.04136	0.99936	0.00006
	70	1.00051	0.01581	-0.00023	0.98695	0.99916	0.00008
RH=30%	40	1.00051	0.0113	-0.00013	0.85643	0.99905	0.00005
	50	1.00051	0.00593	-0.0001	1.04185	0.9991	0.00007
	60	1.00051	0.01136	-0.00041	0.9351	0.99797	0.00019
	70	1.00051	0.00928	-0.00032	1.05756	0.99765	0.00024
RH=40%	40	1.00051	0.00412	-0.00008	1.00999	0.99943	0.00003
	50	1.00051	0.0068	-0.00009	0.97896	0.99936	0.00004
	60	1.00051	0.00933	-0.00017	0.98907	0.99809	0.00013
	70	1.00051	0.01001	-0.0001	1.05997	0.99892	0.00009

Fig. 6 Comparison between the experimental and the predicted data at RH = 20%. **Fig. 8** Comparison between the experimental and the predicted data at RH = 40%. **Fig. 7** Comparison between the experimental and the predicted data at RH = 30%. **Fig. 9** Variation of logarithm of apple moisture ratio with drying time, at RH = 20%.

Fig. 10 Variation of logarithm of apple slices moisture ratio with drying time at RH = 30%.

Fig. 11 Variation of logarithm of apple slices moisture ratio with drying time at RH = 40%.

Table 7 Values of effective diffusivity and activation energy for different drying air conditions.

T °C	Effective diffusivity D_{eff} ($\text{m}^2 \text{s}^{-1}$)		
	RH%		
	20%	30%	40%
40 °C	1.5822×10^{-7}	8.5196×10^{-8}	8.5196×10^{-8}
50 °C	2.1907×10^{-7}	1.3387×10^{-7}	1.0953×10^{-7}
60 °C	2.5558×10^{-7}	2.5558×10^{-7}	1.5822×10^{-7}
70 °C	3.1644×10^{-7}	3.2861×10^{-7}	2.5558×10^{-7}
Activation Energy E_a (kJ/mol)	26.7224088	34.0887987	35.8349736

$$D_{\text{eff}} = D_0 \exp\left(\frac{-E_a}{R.T}\right) \quad (17)$$

Where D_{eff} is the effective diffusivity, D_0 is the constant equivalent to the diffusivity at infinitely high temperature, E_a is the activation energy, R is the

universal gas constant (8.314×10^{-3}) and T is the absolute temperature (in K).

The logarithm of D_{eff} as a function of the reciprocal of the temperature is plotted and fitted by linear regression. The activation energy was calculated from the slope of the straight line described by the Arrhenius equation is varied from 26.72 to 35.83 kJ mol⁻¹. These values are in the range to the values (12.7 to 110 kJ mol⁻¹) reported by Troncoso and Pedreschi for various foods [55].

4. Conclusions

Experimental desorption isotherms of apple slices were determined at 40, 50, 60 and 70 °C, using a static gravimetric methods. The experimental data were successfully fitted by the Peleg model in the investigated temperature and water activity ranges. Tsami's equation was applied to correlate the net isosteric heat of sorption as function of equilibrium moisture content with satisfactory results. From the experimental drying curves obtained, it is noted that only the falling drying rate period exists. Also, the drying air temperature was found to be the main factor influencing the drying kinetics. In this study, the results show that the Midilli et al. model give the best fit. Due to higher number of parameters, this model give better results from the other proposed models based on the solution of the liquid diffusion equation. Midilli et al. model is suitable to predict best the moisture ratio of apple slices in a thin layer dryer at the air temperature T ranges of 40-70 °C, 20%-40% relative humidity range and 2 m s⁻¹ drying air velocity. The calculated effective diffusivities and activation energy ranged from 8.51×10^{-8} to 3.28×10^{-7} m² s⁻¹ and 26.72 to 35.83 kJ mol⁻¹ respectively. The effective diffusivities increased with temperature following the Arrhenius type relationship.

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