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Mathematical Modeling on Vacuum Drying of Olive Pomace

Mouhcine Ibn Maamar[1,*], Mohamed Badraoui[1], Mohamed Mazouzi[1] and Laila Mouakkir[2]

[1] *National High School of Electricity and Mechanics Casablanca, Casablanca, Morocco*
[2] *Ben M'sik Faculty of Science, Université Hassan II de Casablanca, Casablanca, Morocco*

([*]Corresponding author's e-mail: ibnmaamar.ifri@gmail.com)

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Abstract

The thin-layer olive pomace vacuum drying behavior was experimentally investigated for 3 gauge pressures; −130, −200, −250 mbar, and for various sample thicknesses 5, 10 and 15 mm. Nine thin layer mathematical models were used to fit olive cake vacuum drying. Olive pomace vacuum drying took place in the falling rate period at all pressures and for all thicknesses, no constant rate period was observed. Among the selected models, the Diffusion Approach was found to be the most appropriate model better describing the olive pomace drying behavior. The drying rate is correlated to the depression under the thin layer and its thickness. ANOVA-Pareto variance analysis showed the predominance of gauge pressure over layer thickness on drying time and drying rate. The diffusivity coefficient increased linearly over the depression range, from 3.37657E-09 to 4.03063E-06 m^2/s, as obtained using Fick's second law.

Keywords: Olive pomace drying, Vacuum drying, Mathematical modeling, Effective moisture diffusivity, Kinetic model

Introduction

The olive oil extraction industry is of great economic and social importance for all Mediterranean countries where olive cultivation is highly developed. However, this industry generates many worrying environmental problems (pollution of watercourses, groundwater, soil, etc.) due to the pollution generated by its 2 main residues: One liquid (vegetable water) and the other solid (the pomace). The recovery of these by-products, [1,2] would help limit the impact of this industry on the environment [3,4]. Olive pomace represents about 25 % of the olives processed. Its main components are the skin and the crushed pulp of the olive; it still contains a certain amount of fat and a large amount of water, which varies according to the variety of olives and especially the extraction process used. The pomace derived from the pressure system contains a moisture content of about 30 % [5]. However, Continuous 3 and 2-phase centrifugal extraction systems, on the other hand, leave a much wetter pomace with a moisture content of between 45 and 65 % [6]. The main possibilities for upgrading olive pomace, such as solvent extraction of the residual oil, its use as fuel, or as an additive for animal feed, require first the reduction of its water content to values between 5 and 10 % [7]. The drying process is therefore an essential part of its recovery process [7,8].

Most of the olive pomace annually produced is used in dried forms [9,10]. Natural sun and air-drying was the main method traditionally used for olive pomace drying. The Sun-drying process takes 15 days on average and it depends heavily on climate; which affects the economic efficiency of the entire drying process. Recently, olive pomace sun drying is rarely used and it has been replaced by using hot air [11]. Having several advantages over sun drying, hot air drying remains widely used for several fruits and vegetables drying processes. "However, it has several disadvantages, including shrinkage, darkening in color, loss of flavor, and decrease in rehydration ability" [12].

Several other olive pomace-drying processes are used; Vacuum drying is a good alternative method and is particularly suitable for heat-sensitive products, such as fruits and vegetables, and it represents a good economic advantage [11]. "Most vacuum drying uses an oven; it is based on the principle of creating a vacuum to decrease the chamber pressure below the vapor pressure of the water, causing it to boil. With the help of vacuum pumps, the pressure is reduced around the substance to be dried. This decreases the boiling point of water inside the product and thereby increases the rate of evaporation significantly" [13]. Vacuum drying can also be done using filtration, drying occurs by creating a vacuum under the thin layer product, which forces the moisture to move through the filter but not solid particles, especially in capillary porous materials like olive pomace. Despite being newly invented, this process gained popularity because of its ease to use, cost-effectiveness, and economic advantage.

Several studies have been undertaken on vacuum oven drying of fruits and vegetables [14,15], however, to our knowledge, there is no available report regarding olive pomace vacuum drying using the filtration process. Little or no information is available on drying rates, diffusivity, and mathematical models describing the process of olive pomace vacuum drying. The absence of such information makes the design of dryers and the determination of optimal drying conditions very difficult. Therefore, drying kinetics and drying kinetics models determination is essential for quality improvement of dried olive pomace, and the drying process optimization.

The aim of this work is to describe the optimum conditions of olive pomace vacuum drying using filtration principal, and to evaluate, based on 9 existing mathematical models, a suitable drying model better describing the vacuum drying process.

Material and methods

Materials

The pomace samples come from an oil mill operating with the 2-phase continuous centrifugation system. Its main characteristics are the average initial humidity equal to 66 % wet basis and a density equal to 0.90 g.mL-1.’, the average particle diameter equal to 1.96 mm, and the average oil content is 5.50 % dry basis.

Drying experiments

Pomace samples were dried by creating depression under the thin layer, as given in **Figure 1**. The schematic diagram of the vacuum drying unit consists of a reservoir (2) on which the thin layer (7) is deposited, connected to a reservoir (4) placed under vacuum by a vacuum pump (3). The under-pressure is regulated using a valve (1). The depression is measured by a vacuum gauge (6) placed on the tank. Once the drying depression is reached, place the sample while triggering the stopwatch. Measure the weight of the assembly (carrier + sample) using a precision balance (0.01 g). The room temperature was kept constant during the experiment.

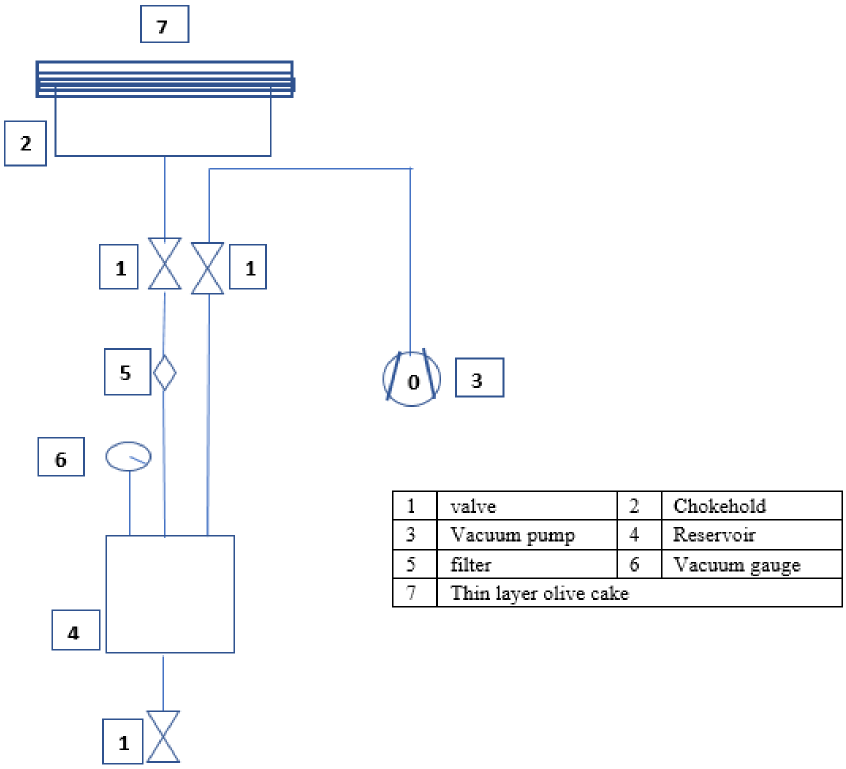


Figure 1 Schematic diagram of the vacuum drying unit.

The drying kinetics is studied for 3 gauge pressures (−130, −200 and −250 mbar) and for 3 different thicknesses (5, 10, 15 mm^3). For all the experiments, the relative humidity of the ambient air ranged from 55 to 60 %. Every 10 min the batch of samples is weighed using an electronic balance. The drying experiment is stopped when the desired final water content is reached (approximately 12 %). The dried product is then placed in an oven at a temperature of 120 °C until a constant weight is obtained to determine its dry weight.

Mathematical modeling

Nine well-known thin-layer semi-empirical and empirical mathematical models given in the literature [16] were used to describe the vacuum drying kinetics of olive pomace (**Table 1**). In these models, MR represents the moisture ratio (dimensionless) calculated using the following equation:

$$\mathrm{MR} = \frac{(M_t - M_e)}{M_0 - M_e} \quad (1)$$

where "M_t, is the water content at time **t** (kg water/ kg dry matter), M_e, the equilibrium water content (kg water/kg dry matter), and M_0, the initial water content (kg water/kg dry matter)" [17]. The values of M_e are negligible compared with M_0 and M_t [18,19], thus, Eq. (1) can be reduced to:

$$\mathrm{MR} = \frac{Mt}{M0} \quad (2)$$

"Non-linear least square regression analysis was performed using the Levenberg-Marquardt procedure in SigmaPlot" [12]. The criteria for evaluating the quality of smoothing of the experimental results are "the coefficient of determination (R^2), the root mean square error (RMSE), and the reduced ki-square (χ^2)" [20]. These parameters are calculated according to the relations:

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(\mathrm{MR_{ei}} - MR_{pi}\right)^2}{\mathrm{N-Z}} \quad (3)$$

$$RMSE = \left[\frac{1}{\mathrm{N}} \sum_{i=1}^{N} \left(\mathrm{MR_{ei}} - MR_{pi}\right)^2\right]^{1/2}$$

$\mathrm{MR_{ei}}$, is the ith experimental value, MR_{pi}, the ith value predicted by the model, N, the number of observations, and Z, the number of constants in the model [21].

The coefficient of determination R^2 is the first criteria for evaluating the quality of smoothing of experimental results. The model which best describes the drying kinetics is the one for which the value of R^2 is the highest and the values of χ^2 and RMSE are the lowest [22].

Table 1 Thin-layer semi-empirical and empirical mathematical models.

Model name	**Model**
Newton	MR = exp(−kt)
Henderson & Pabis	MR = a exp(−kt)
Page	MR = exp(− $(kt)^n$)
Wang & Singh	MR = 1 + at + bt^2
Two terms exponential	MR = a exp(−kt) + (1 – a) exp (−Kat)
Diffusion approach	MR = a exp(−kt) + (1 – a) exp (−Kbt)
Logarithmic	MR = a exp(−kt) + c
Two terms	MR = a exp (−kt) + b exp (−K’t)
Modified henserson & Pabis	MR = a exp (−kt) + b exp (−K’t) + c exp (−K’’t)

Effective moisture diffusivity

"The effective moisture diffusivity is derived from Fick's second law of diffusion Eq. (5), Fick's second law of diffusion describes the rate of accumulation (or decay) of concentration within a volume as proportional to the local curvature of the concentration gradient. The local accumulation rule follows Fick's second law of diffusion which illustrates the movement of moisture within the solid" [23].

$$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M \qquad (5)$$

D_{eff} is the effective moisture diffusivity (m^2/s), M, the moisture content (kg/kg of dry solid), and t is the drying time (s). Assuming moisture migration is controlled by diffusion, and an infinite slab of thin layer, Fick's law can be developed in the form of the following equation:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2}{4L^2}D_{eff}t\right] \qquad (6)$$

"D_{eff} is the effective moisture diffusivity (m^2.s^{-1}), and L is the half-thickness of the slab product being dried (m)" [24].

For a long drying time, only the first term of the series (n = 0) gives a good estimate of the solution. Thus, simplified Eq. (6) is expressed in a logarithmic form as follows:

$$Ln(MR) = Ln\left(\frac{8}{\pi^2}\right) - D_{eff}\left(\frac{\pi}{2L}\right)^2 t \qquad (7)$$

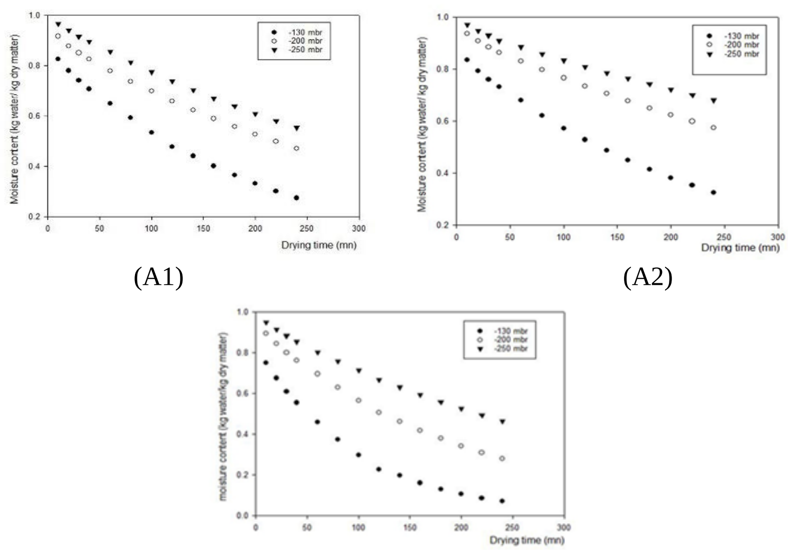
The effective moisture diffusivity is determined by noting the slopes of a straight line. From Eq. (7), a plot of experimental data in terms of $Ln(MR)$versus time gives a straight line with a slope of:

$$Slope = -D_{eff}\left(\frac{\pi}{2L}\right)^2 \qquad (8)$$

Results and discussion

Analysis of the drying curves

The kinetic curves of vacuum drying of olive pomace for different gauge pressures and thicknesses are shown in **Figure 2**. These curves express the evolution of the reduced water content as a function of time.



(A1) (A2)

(A3)

Figure 2 Effect of vacuum drying and layer thickness on the moisture content of olive pomace; (A1) 5 mm thickness, (A2) 10 mm thickness, and (A3) 15 mm thickness.

The results show that the depression under the thin layer, and the layer thickness significantly influence the drying time of olive pomace. An increase in the gauge value of the depression, or a decrease in the thickness results in a reduction in the drying time of the product. The depression under the thin layer is reversely correlated to values indicated by the vacuum gauge (6) **Figure 1** since valve (1) reduces the amount of air the vacuum pump (3) can absorb, which creates more vacuum in the reservoir (4) resulting in an increase in the vacuum gauge values. Indeed, Analysis of variance (ANOVA-Pareto) applied to analyze the contribution of each of the optimized parameters show the predominance of the depression under the olive pomace thin layer with a contribution of 46 % followed by the thickness of the thin layer (29 %), the remaining (26 %) is related to the third factor which is the drying time.

Figure 3 describes the evolution of the drying speed as a function of the reduced water content for gauge pressures and thicknesses ranging respectively from −130 to −250 mbar, and 5 to 15 mm.

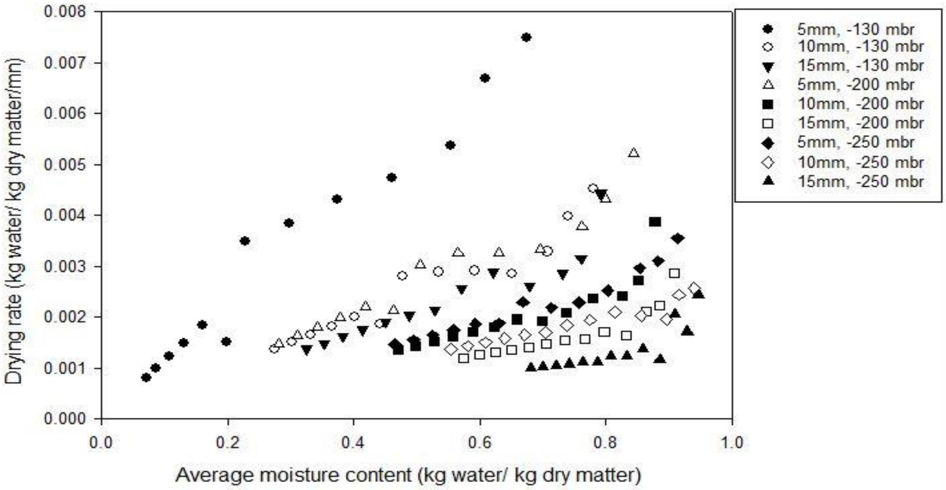


Figure 1 Drying rate curves of olive pomace determined at different gauge pressures and layer thicknesses.

The drying speed continuously decreases with the average moisture content of the product but increases with the depression under the thin layer. The shape of the curves indicates the absence of a constant drying rate period. Therefore, only the period with decreasing rate or period of slowing down is observed. Similar results have been obtained in thin-layer drying of other biomaterials, such as *Zizyphus jujuba* Miller [12], Monukka seedless grapes [25], orange slices [26], dried carrot [27], and whole-fruit Chinese jujube [28].

During this drying phase, the process of transferring water from the product is mainly governed by diffusion [29]. These observations are in agreement with those published in the literature for drying olive pomace [24,30,31] and for other biological products [14,22].

Modeling

The moisture contents of the olive pomace thin layer at different drying pressures were converted to dimensionless moisture ratio (MR) and fitted to the 9 selected thin-layer drying models listed in **Table 1**. The values of the determination coefficient (R^2), the root mean square error (RMSE), and the reduced chi-square (χ^2) determined by nonlinear regression analysis are reported in **Table 2**. The values vary respectively from 0.6381 - 0.99997, 8.5725E-07 - 0.00437143 and 0.0006466 - 0.06184658 for R^2, χ^2, and RMSE. The high values of R^2 and the low values of χ^2 and RMSE indicate a good fit of all these models to the experimental results.

Among these models, ‘Diffusion Approach’ followed by ‘Two Terms’ Give the highest values of the coefficient of determination (greater than 0.9982) and the lowest values of χ^2 and RMSE (respectively less than 10^{-4} and 0.00707) for the different pressures and thicknesses studied. The Modified Henderson & Pabis model that gives high values of R^2 for thicknesses above 10mm comes third. The given model has also been proposed by others to describe thin layer microwave drying of olive pomace [24,31].

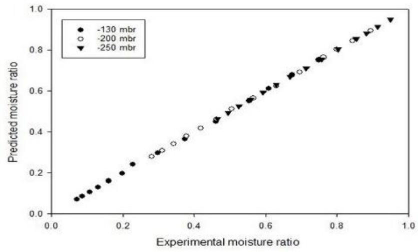
Table 2 Statistical results obtained from different thin layer drying models.

Model	Gauge pressure (mbar)	Thichnes (mm)	R^2	CHI^2	RMSE
Newton	−130	5	0.8728	0.00437143	0.06184658
		10	0.7048	0.00437143	0.06184658
		15	0.6381	0.00432857	0.06154267
	−200	5	0.9505	0.00092857	0.02850439
		10	0.8545	0.00118571	0.03221025
		15	0.9208	0.00075714	0.02573908
	−250	5	0.9806	0.00018571	0.01274755
		10	0.9934	0.00004286	0.00612372
		15	0.9516	0.00015714	0.01172604
Henderson & Pabis	−130	5	0.9982	0.00006667	0.00707107
		10	0.9985	0.00003333	0.00500000
		15	0.9988	0.00001665	0.00353377
	−200	5	0.9989	0.00001667	0.00353553
		10	0.997	0.00003333	0.00500000
		15	0.9964	0.00001667	0.00353553
	−250	5	0.9987	0.00001457	0.00330590
		10	0.9997	0.00000229	0.00131106
		15	0.993	0.00003333	0.00500000
Logarithmic	−130	5	0.9994	0.00004000	0.00500000
		10	0.9986	0.00002000	0.00353553
		15	0.9988	0.00001923	0.00346659
	−200	5	0.999	0.00002000	0.00353553
		10	0.9988	0.00001318	0.00286995
		15	0.9986	0.00000966	0.00245698
	−250	5	0.9993	0.00000919	0.00239659
		10	0.9997	0.00000275	0.00131044
		15	0.9975	0.00001138	0.00266676
Modified Henderson & Pabis	−130	5	0.9982	0.00020000	0.00707107
		10	0.9985	0.00010000	0.00500000
		15	0.9996	0.00001879	0.00216749
	−200	5	0.9989	0.00005000	0.00353553
		10	0.9999	0.00000167	0.00064660
		15	0.9999	0.00000171	0.00065469
	−250	5	0.9998	0.00000603	0.00122755
		10	0.9997	0.00000686	0.00130944
		15	0.9994	0.00000727	0.00134829
Wang & Singh	−130	5	0.9989	0.00006000	0.00612372
		10	0.9984	0.00004000	0.00500000
		15	0.9988	0.00002000	0.00353553
	−200	5	0.9988	0.00004000	0.00500000
		10	0.9985	0.00001667	0.00322827
		15	0.9983	0.00001175	0.00270945
	−250	5	0.9992	0.00001175	0.00271035
		10	0.9997	0.00000290	0.00134699
		15	0.997	0.00001365	0.00292047

Model	Gauge pressure (mbar)	Thichnes (mm)	R^2	CHI^2	RMSE
Two terms exponential	−130	5	0.9593	0.00163333	0.03500000
		10	0.8754	0.00215000	0.04015595
		15	0.8386	0.00225000	0.04107919
	−200	5	0.9931	0.00015000	0.01060660
		10	0.9594	0.00038333	0.01695582
		15	0.9568	0.00025000	0.01369306
	−250	5	0.9998	0.00000207	0.00124655
		10	0.9978	0.00001667	0.00353553
		15	0.9967	0.00001227	0.00303307
Page	−130	5	0.9842	0.00063333	0.02179449
		10	0.9817	0.00031667	0.01541104
		15	0.9831	0.00023333	0.01322876
	−200	5	0.9943	0.00013333	0.01000000
		10	0.9964	0.00003333	0.00500000
		15	0.9968	0.00001667	0.00353553
	−250	5	0.9993	0.00000797	0.00244459
		10	0.9991	0.00000711	0.00230949
		15	0.9986	0.00000529	0.00199202
Two terms	−130	5	0.9982	0.00010000	0.00707107
		10	0.9985	0.00005000	0.00500000
		15	0.9996	0.00000940	0.00216752
	−200	5	0.9989	0.00002500	0.00353553
		10	0.9999	0.00000110	0.00074254
		15	0.9999	0.00000086	0.00065469
	−250	5	0.9998	0.00000301	0.00122755
		10	0.9997	0.00000341	0.00130638
		15	0.9994	0.00000364	0.00134829
Diffusion model	−130	5	0.9982	0.00008000	0.00707107
		10	0.9988	0.00002000	0.00353553
		15	0.9995	0.00000803	0.00224042
	−200	5	0.9992	0.00002000	0.00353553
		10	0.9999	0.00000094	0.00076820
		15	0.9998	0.00000118	0.00086046
	−250	5	0.9998	0.00000244	0.00123592
		10	0.9998	0.00000178	0.00105549
		15	0.9992	0.00000354	0.00148703

Therefore, the ‘Diffusion Approach’ model is the one that best captures the behavior of thin-layer vacuum drying of olive pomace.

“Newton” model appears to be the one that gives poor fits with the experimental results in all of the studied cases.



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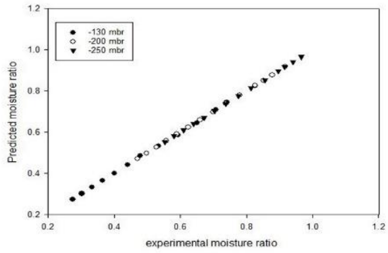

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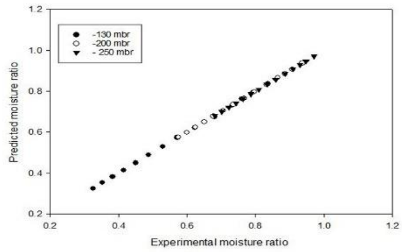

(A3)

Figure 2 Comparison of moisture ratios obtained by experimentation and prediction using the diffusion approach model for various pressures and thicknesses; (A1) 5 mm thickness, (A2) 10 mm thickness, and (A3) 15 mm thickness.

As shown in **Figure 4**, the proposed model provides similar results between the experimental and predicted moisture ratios for the different studied cases. The 45 ° line illustrates the conformity of the chosen model.

Effective moisture diffusivity

In the literature, no report treats the effective moisture diffusivity (D_{eff}) for olive pomace thin layer vacuum drying using the filtration process. The effective moisture diffusivity values for different gauge pressures and layer thicknesses of the pomace were estimated using the method of the slope derived from the linear regression $Ln(MR)$ versus drying time Eq. (8) [17,32]. The plots give straight lines with high determination coefficients R^2 ranging between 0.99916 and 0.99996. As expected, the effective diffusivity values obtained of dried olive pomace samples increase with increasing the depression under the thin layer and the thickness of the sample. The Deff values, presented in **Table 3**, ranged from 3.37657E-09 - 4.03063E-06 m^2/s.

Table 3 Effective diffusivity values for olive pomace.

Gauge pressure (mbar)	Thickness (mm)	D_{eff}	R^2
−130	5	1.1324E-08	0.99921119
	10	2.095E-08	0.9997151
	15	4.0306E-06	0.99991394
−200	5	5.5262E-09	0.99980735
	10	1.25E-08	0.99994153
	15	2.0566E-06	0.9998584
−250	5	3.3766E-09	0.9998991
	10	1.0608E-08	0.99996818
	15	1.4877E-06	0.99916489

These values are similar to diffusivities obtained for wolfberry 5.23E-09 [33], Lee and Kim for vacuum drying of Asian white radish, Swasdisevi for drying banana slices using combined far-infrared and vacuum drying,

Moreover, D_{eff} values are in agreement with those obtained for other olive pomace drying processes; microwave drying 3.55E-09, air drying 2.81E-07, thin-layer infrared drying of wet olive husk. The same results were observed for fresh apple pomace, microwave drying of white mulberry, and potato slices, and for infrared drying of industrial grape by-products.

Conclusions

1) The kinetics of thin-layer vacuum drying of olive pomace is studied for different pressures and thicknesses.

2) The pomace drying process took place at a falling rate, no constant rate was observed for all parameters studied. The drying time decreases significantly with depression under the thin layer and the sample thickness.

3) Among the semi-empirical and empirical mathematical models used, the "Diffusion Approach" model seems the most appropriate to describe the behavior of olive pomace vacuum drying under experimental conditions.

4) The highest value of the determination coefficient R^2 and the lowest values of the root mean square error RMSE, and reduced chi-square (χ^2) were observed for 15 mm thin layer thickness and gauge pressure of −200 mbar.

5) The calculated effective diffusivities ranged from 3.37657E-09 - 4.03063E-06 m^2/s, increasing with an increase in both the depression under the thin layer and the sample thickness.

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