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Research Article

# THIN LAYER DRYING STUDY OF *ACORNS* (*Quercus ilex* L.) -NEW MATHEMATICAL MODELLING APPROACH

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## ABSTRACT

The thin layer drying behaviour of *acorns* was investigated at three oven temperatures (60, 70 and 80 °C). The drying kinetic was fitted and modelled using different mathematical drying models. The use of First-Order (FO) and Pseudo-First-Order (PFO) was proposed and estimated for describe the moisture content evolution of *acorns* as a function of time. According the coefficient of determination ($R^2$), the root mean square error (*RMSE*) and the sum mean of square error ($\chi^2$), the best fit was given by the Logarithmic model. A good fit ($R^2 > 0.9942$; $RMSE < 2.238$ and $\chi^2 < 6.014$) was shown by FO and PFO indicating their aptitude to describe the thin layer drying kinetic of *acorns*. Effective moisture diffusivity increased from $4.016\times10^{-8}$ to $1.244\times10^{-7}$ m² s$^{-1}$ with the rice of drying temperature. The elimination of water from the *acorns* requires an activation energy of about 55 kJ mol$^{-1}$.

**Keywords:** adsorption; kinetic; microorganisms; moisture; mathematical model; traditional couscous.

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## 1. INTRODUCTION

Drying is the operation which aims to eliminate, by evaporation, water from a wet body; the final product obtained always being a solid. Its application is known in many fields, particularly in the food industry where the essential aim is the stability of food by the reduction in water activity.

The thin layer is characterised by a transfer rapid of mass and heat, and considered as economic method. Drying mathematical modelling is necessary for understanding the drying behaviour of food material. Thus, drying kinetic model is used to predict and simulate drying process, and for the design of dryers and specialized equipment [1,2]. Many drying kinetic models have been requested to describe thin layer drying characteristics of different agricultural products [3-7].

It is admitted that the majority of the physicochemical reactions taking place in food obey a kinetic law of order one and that the concept of reaction can be extended to physicochemical phenomena like the vaporization of water during drying [8].

The present study aims to determine and model mathematically the drying kinetics of *acorns* (*Quercus ilex* L.), known for their interesting therapeutic and food values [9]. In Algeria, these fruits were one of the staple foods for many Algerians during the period of colonization, and even after independence, during the famine crises that affected Algeria. At present, *acorns* are used in particular for their diversified therapeutic virtues [9]. They are used to prepare traditional dishes, such as the couscous known locally by the name 'Taam elballout', where a considerable amount of *acorn* flour (about one third) is mixed with the other of constituents.

Two models, 'first order' (FO) and 'pseudo first order' (PFO) were proposed to describe the drying kinetics. The possibility of use of the PO model comes from the fact that the reduction of humidity by drying can be described by analogy with physicochemical phenomena like the thermal destruction of microorganisms or inactivation of enzymes [8]. Used in the description of the adsorption process [10], the PPO model was adapted in this study to predict the drying kinetics.

## 2. RESULTS AND DISCUSSION

### 2.1. Experiments curves of thin layer drying

The thin layer drying curves of *acorns* at the different drying temperatures tested are presented in Figure 1. According to this figure, the curves of the drying kinetics are characterized by a lower and lower drop in the moisture content which was reduced from an initial value of 53.61% (db) to 0.153%, 0.31% and 0.307%, respectively, for 60, 70 and 80 °C. The curves are marked by an absence of the constant rate drying period and are composed only of a single period which is the drying phase at decreasing rate**.** The drying time was of 60, 90 and 150 min respectively for 60, 70 and 80 °C. The constant rate period is not observed for many biological products [21,22]. Bimbenet et al. [8] reported that the short initial setting period disappears when the product is in particles or leaves. This behaviour of the product on drying is explained by the low presence of water on the product surface, so it is the internal diffusion of water that is predominant [20]. The drying can occur predominantly during the period of decreasing rate [1]. It should be noted that several authors have revealed that it is difficult to locate the constant rate drying period in the case of biological products and that the action of relative humidity on drying is not significant in the absence of this phase [23]. The drying time is influenced by several factors, such as the temperature, the initial moisture content, drying method and the products nature [1,20].

Drying behaviour has been investigated for many agricultural products where the models used for the description of the behaviour can be variable according the nature of the product and the drying method used [12, 24-26].

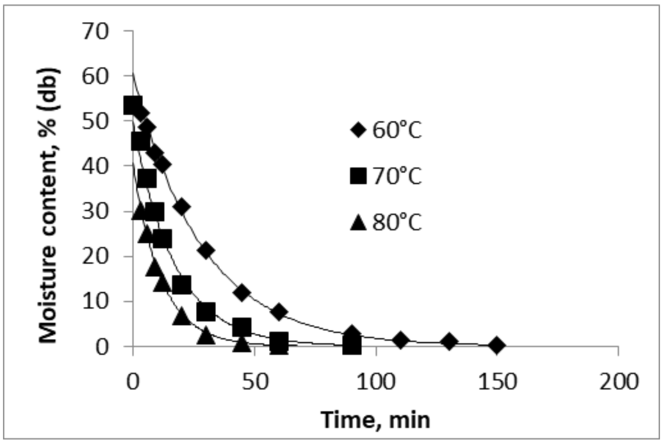

**Fig.1.** Thin layer drying curves of *acorns* at different temperatures

### 2.2. Modelling of thin-layer drying

The moisture ration curves are often preferable because they are more appropriate to describe the drying characteristics foodstuffs [3]. For the different temperatures considered, the experimental moisture contents were converted into rations and presented in Figure 2. The kinetic and statistical parameters of non-linear analysis of the fitting of the models tested to the thin layer drying data for *acorns* at the different temperatures considered are grouped in Table 1.

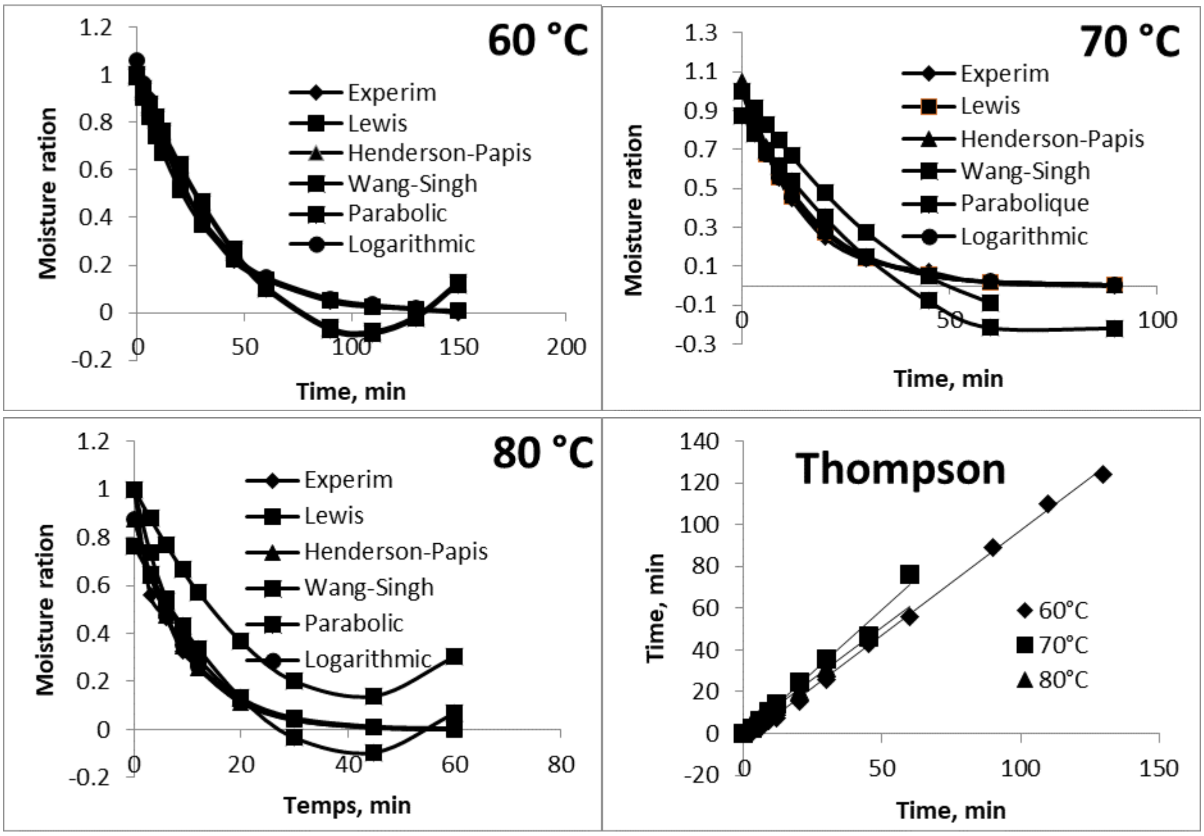

**Fig.2.** Experimental curves and predicted by the different models tested of the moisture ration

**Table 1.** Kinetic and statistical parameters of thin layer drying models for *acorns*

| Model | Temp, °C | $K_i^{(*)}$ | a | b | c | *RMSE* | $\chi^2$ | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| Lewis | 60 | 0.033 | | | | 0.0455 | 0.0025 | 0.9971 |
| | 70 | 0.065 | | | | 0.0155 | 0.0003 | 0.9894 |
| | 80 | 0.1020 | | | | 0.0696 | 0.0062 | 0.9970 |
| Henderson-Pabis | 60 | 0.0331 | 1.0584 | | | 0.0344 | 0.0013 | 0.9970 |
| | 70 | 0.065 | 0.0533 | | | 0.0292 | 0.0010 | 0.9895 |
| | 80 | 0.1020 | 0.1351 | | | 0.0151 | 0.0033 | 0.9970 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Logarithmic | 60 | 0.031 | 1.054 | 0.00547 | | 0.0151 | 0.0004 | 0.9972 |
| | 70 | 0.0613 | 0.9999 | 0.0015 | | 0.0154 | 0.0002 | 0.9896 |
| | 80 | 0.0961 | 0.8734 | 0.0031 | | 0.0514 | 0.0033 | 0.9970 |
| Thompson | 60 | | 0.9223 | 26.735 | | 3.499 | 14.69 | 0.9981 |
| | 70 | | 0.4315 | 16.954 | | 5.9020 | 34.8347 | 0.9907 |
| | 80 | | 0.030 | 9.6101 | | 1.4148 | 2.2876 | 0.9970 |
| Wang-Singh | 60 | | 0.0001 | 0.0208 | | 0.0669 | 0.0053 | 0.9864 |
| | 70 | | 0.0002 | 0.0301 | | 0.1415 | 0.0250 | 0.9381 |
| | 80 | | 0.0005 | 0.0416 | | 0.2382 | 0.0729 | 0.8776 |
| Parabolic | 60 | | 0.0001 | 0.0208 | 0.9891 | 0.0191 | 0.0004 | 0.9972 |
| | 70 | | 0.0002 | 0.301 | 0.9381 | 0.1298 | 0.0210 | 0.9381 |
| | 80 | | 0.0005 | 0.0416 | 0.7643 | 0.1056 | 0.014 | 0.8776 |

(*) $k_i$= constants kinetic; a, b and c = coefficients; *RMSE*, $\chi^2$ and $R^2$ = statistical parameters.

In the study carried out by Akpinar and Bicer [27], among thirteen different mathematical models, Logarithmic model was found the most suitable for describing the curve of the thin layer solar drying process of long green peppers ($R^2$ of 0.98815, $\chi$ 2 of 0.0017 and *RMSE* of 0.0409). With high values of the coefficient of determination ($R^2 > 0.965$), Logarithmic, Lewis and Henderson-Pabis models were appropriate to describe the drying curves of Jew’s mallow leaves [20] and *dika* kernels and nuts [1]. According $R^2$ and $\chi^2$ varying from 0.9929 to 0.9979 and from $9.65.10^{-3}$ to $141.10^{-3}$, respectively, the Lewis and Henderson-Pabis models also showed a good suitability for the description of thin-layer drying of whole bananas after Page and Silva et alii models which seem the most adequate [24].

For the same temperatures (60, 70 and 80 °C), Hii, Law and Cloke [28] proved that the new model was best fit for the thin layer drying behaviour of Cocoa beans. The Page model was selected as the most appropriate to modelling thin layer drying behaviour of potato slices [29]. Midilli-Kucuk drying model showed the best fitting in describing the drying behaviour of *Vernonia amygdalina* leaves at 40, 50 and 60 °C [30]. In the mathematical modelling study of hot air drying for some agricultural products investigated by Waewsak, Chindaruksa and Punlek [31], the Wangh-Singh model was the most suitable for lemon grass, where the Midilli model was found to be the best for describing the drying behaviour of red chili peppers and leech lime leaves.

### 2.3. Effective diffusivity and activation energy of thin layer drying of *acorns*

Figure 3 shows the influence of oven temperature on the effective moisture diffusivity of *acorn*s ($D_{eff}$, $m^2 s^{-1}$). An increase in $D_{eff}$ from $4.016\times10^{-8}$ to $1.244\times10^{-7}$ $m^2 s^{-1}$ was observed when the drying temperature increased from 60 to 80 °C. According to the coefficient of determination ($R^2 = 0.9977$), 99.77% of data are represented by the following linear relationship: $D_{eff} = 4\times10^{-9}\ T - 2\times10^{-7}$. The increase in $D_{eff}$ during *acorns* drying is attributed to the improved water migration exerted by the increase in internal vapour pressure under the effect of increasing of the drying temperature [32]. Several studies have reported the increase of $D_{eff}$ under the drying temperature [1, 2, 20, 25]. The values of the effective moisture diffusivity of *acorn*s were above appropriate values for most fruits and vegetables [33], while they were consistent with the values within the range of $10^{-12}$ to $10^{-8}$ $m^2 s^{-1}$ that has been reported for agricultural and food products [20, 34, 35].

From the plot of $\ln(D_{eff})$ against the absolute temperature (Fig. 3), the activation energy was found to be 55.33 KJ $mol^{-1}$.

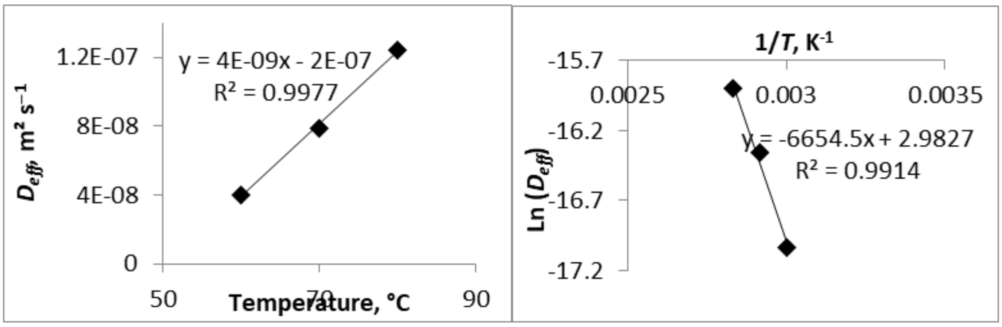

**Fig.3.** Effect of oven temperature ($T$, K) on the effective moisture diffusivity ($D_{eff}$, $m^2 s^{-1}$) of *acorns*

The activation energy value was within the range (12.7 – 110 KJ $mol^{-1}$) of a typical drying operation [36] and the range (12.87–58.15 KJ $mol^{-1}$) of most food crops [37]. The activation energy was calculated also by the plotting of $\ln(K_3)$, constants relating to the Logarithmic model, against the reverse of the absolute temperature. The value found (55.38 KJ $mol^{-1}$) was similar to that (55.33 KJ $mol^{-1}$) shown above. This is another confirmation of the fit of the model to the experimental data. Moisture removal from *acorns* requires higher activation energy compared with many agricultural products such as tomato slices [25, 38], *dika* nuts and kernels [1], Pistachio [39], Cashew nuts [40] and Cab Franc grape seed [41].

### 2.4. Modelling approach of drying kinetic

Figure 4 illustrates the experimental curve of the moisture content evolution as a function of time compared to those plotted using the FO and PFO models at the three temperatures tested.

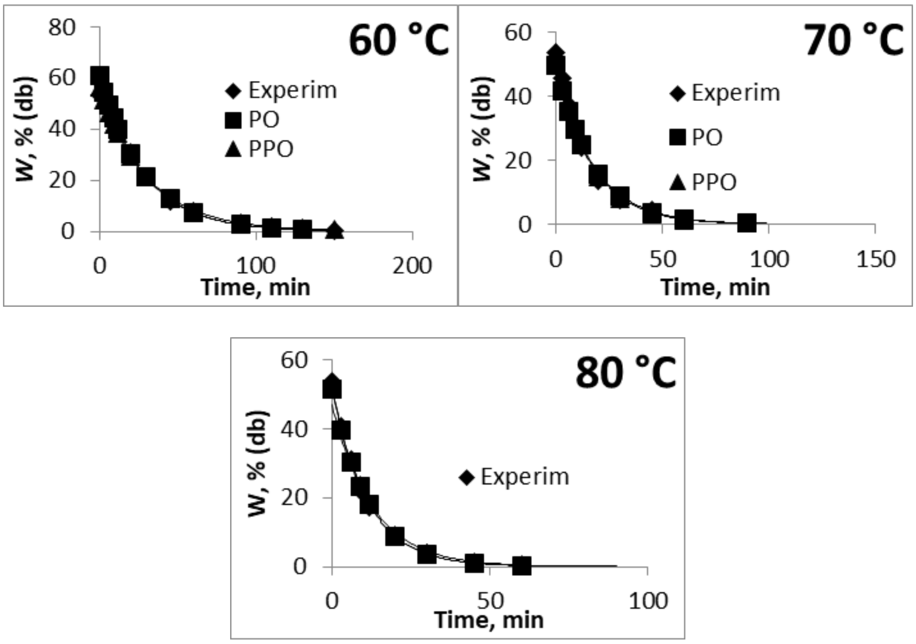

**Fig.4.** Experimental curve compared to the curves predicted by the models First-Order (FO) and Pseudo-First-Order (PFO) of the moisture content evolution (*W*, % (db)) of *acorns* as a function of time

For the three temperatures considered, it is easy to remark the superposition of the curves predicted by the two models proposed on the experimental curve. This is confirmed by the very high values of the coefficients of determination ($R^2 > 0.9942$ for PO; $R^2 > 0.9972$ for PPO) relating to the straight lines described by the linear equations, and the very low values of $\chi^2$ and *RMSE* ($\chi^2 < 6.014$; for FO and $\chi^2 < 2.371$ for PFO) (Table 2).

**Table 2.** Modelling of drying kinetic of *acorns* using First-Order and Pseudo-First-Order models

| Model | Temp, °C | *K*, % $min^{-1}$ | *D-value*, min | *RMSE* | $\chi^2$ | $R^{2(*)}$ |
|---|---|---|---|---|---|---|
| First-Order | 60 | 0.035 | 69.787 | 2.238 | 6.014 | 0.9959 |
| | 70 | 0.058 | 35.705 | 2.038 | 5.159 | 0.9942 |
| | 80 | 0.088 | 25.818 | 0.927 | 1.105 | 0.9963 |
| Pseudo-First-Order | 60 | 0.035 | 69.787 | 1.405 | 2.371 | 0.9972 |
| | 70 | 0.058 | 35.705 | 0.881 | 0.997 | 0.9896 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 80 | 0.088 | 25.818 | 0.898 | 1.129 | 0.9985 |
| Logarithmic | 60 | | 74.290 | | | |
| | 70 | | 37.569 | | | |
| | 80 | | 23.964 | | | |

(*)*K*: Constant kinetic; *D-value*: decimal reduction time; *RMSE*, $\chi^2$ and $R^2$ = Statistical parameters. For comparison purposes, the Logarithmic model is also inserted here.

The finding is also validated by the very high correlation ($R^2 > 0.9939$) between the experimental and predicted values (Fig. 5). Consequently, the FO and PFO models are adequate and suitable for predicting the drying kinetic of *acorns* in the form of the moisture content variation as a function of time using oven drying method in the temperature range from 60 to 80 °C.

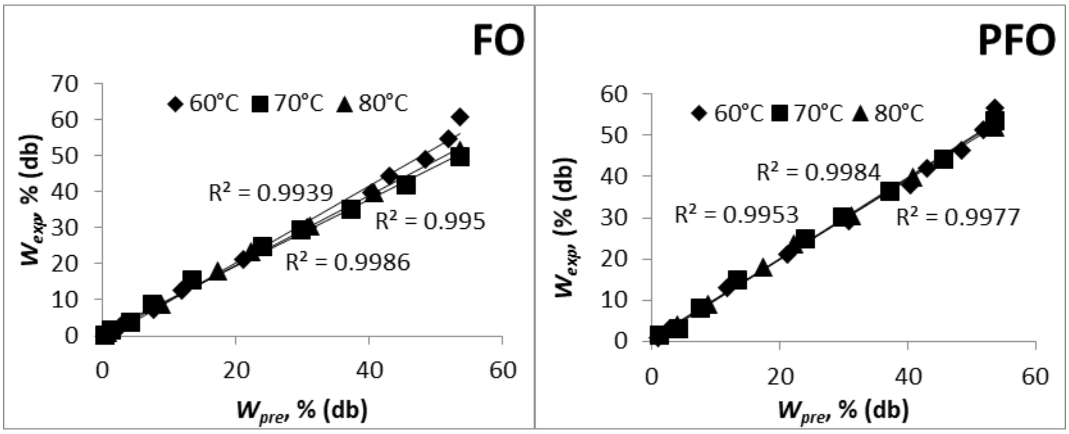

**Fig. 5.** Correlation between experimental ($W_{exp}$, % (db)) and predicated ($W_{pre}$, % (db)) values of moisture content using First-Order and Pseudo-First-Order models at three temperatures tested

It should be noted that Bimbenet et al. [8] proposed the use of FO model for describe the drying modelling of products in its original dimension.

On the other hand, the results showed an increase in the constants ($k$) as drying temperature raised. The increase in constants under the effect of the temperature expresses the increase in the drying rate due to the rise in the diffusivity of the *acorns* water, linked in turn, to the temperature elevation. Similar results were reported in some studies [1, 20, 25].

### 2.4.1. Activation energy

Using the Arrhenius relationship, the activation energy of oven drying of *acorns* was calculated, in this part, from the slope of the plot of ln($K$) against absolute temperature shown in Figure 6.

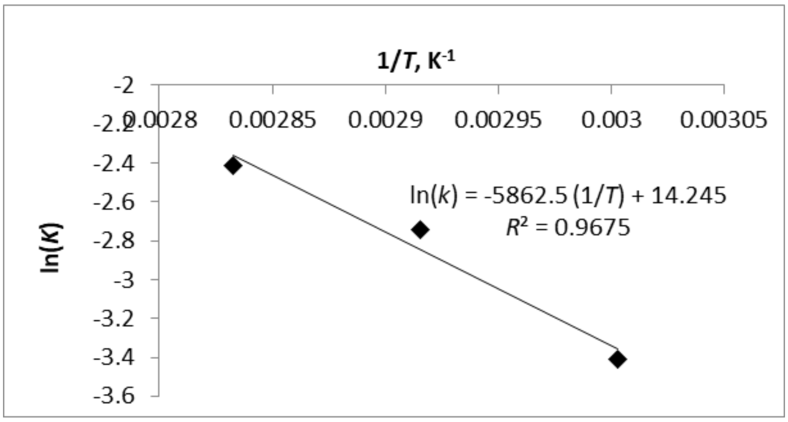

**Fig. 6.** Plot of ln($K$) against the reverse of the absolute temperature ($T$, K) for acorns

**Table 3.** Effect of temperature on the drying *acorns*

| Model | $E_a$, KJ mol$^{-1}$ | $Q_{10}$ | *Z-value*, °C |
|---|---|---|---|
| First-Order$^{(*)}$ | 48.741 | 1.668 | 19.528 |
| Logarithmic | 55.380 | 1.772 | 17.469 |

$^{(*)}$ First-order and Pseudo-First-Order models gave the same values of the constants $K$. The temperature coefficient ($Q_{10}$) and the temperature elevation (*Z-value*, °C) are calculated by the average of two consecutive reports.

Table 3 indicate that according to the prediction of the proposed models, the elimination of water from the *acorns* requires an $E_a$ of about 50 kJ mol$^{-1}$. This value slightly lower than that (55 KJ mol$^{-1}$) calculated using the prediction of the Logarithmic equation.

### 2.4.2. Decimal reduction in the initial moisture content and in the time drying

By similarity to the thermal destruction of microorganisms [8], it is possible to determine the decimal reduction time which represents the time (*D-value*, min) necessary for the reduction of the initial moisture content by 90% and the rise in temperature (*Z-value*,°C) which enable to reduce the drying time by 90%. The time *D-value* was calculated from the kinetic constant ($K$) according to the equation (1) [8].

$$D - value = 2.303/K \qquad (1)$$

while *Z-value* was calculated using the following expression:

$$Z - value = 10/\ln(Q_{10}) \qquad (2)$$

$Q_{10}$ is the coefficient of temperature which was calculated according the equation (3).

$$Q_{10} = K_{T+10}/K_T \qquad (3)$$

where $k_T$ and $k_{T+10}$ the kinetic constant $k$ determined respectively at temperatures $T$ and $T$+10°C.

From the Table 3, the results show that *D-value* decreases from 25.818 to 69.787 min when the applied temperature rise from 60 to 80 °C. The values of *D-value* deduced from the constants predicted by these laws were comparable to those calculated from the prediction of the Logarithmic model; this is another confirmation of the use of the proposed models to describe the drying kinetic of *acorns*. The values of *D-value* decrease with temperature which is consistent with theoretical predictions. But it seems that the reduction is not of the same intensity on the temperature scale. Indeed: $D_{70}/D_{60}$ = 0.51 and $D_{80}/D_{70}$ = 0.72. These observations lead us to think that the decimal reduction time *D-value* is very sensitive to the action of temperature.

To be reduced by 90% of the initial value, the drying time of the *acorns* requires a *Z-value* of about 19 °C according to the experimental conditions of the present drying method (Table 4). The *Z-value* for water removal from *acorns* are significantly lower than the *Z-value* of the vitamin A degradation in heat treated carrot juice in the range of 104 – 132 °C or vitamin C of a juice prepared from grapefruit and pasteurized in the range of 61 – 96 °C [42]; whereas, according to these same authors, *Z-value* is more superior to the values that characterize the thermal destruction of different microorganisms such as *Bacillus stearothermophilus*, *Clostridium botulinum* and *Clostridium thermosacharolyticum*.

$E_a$, *D-value*, $Q_{10}$ and *Z-value* express the effect of temperature on the drying rate and reflect the sensitivity of the product to treatment; they can be useful in the optimization operation.

## 3. EXPERIMENTAL METHODOLOGY

### 3.1. Preparation of *acorns*

The *acorns* (about 10 kg) studied in the present study were bought in the market of

Boumerdès (Algeria) in January, 2022. Sold in bulk, the samples are made up of a multitude of varieties. *Acorns* are fruits of the holm oak pertaining to the family of *Fagaceae*, the genus is *Quercus and* the species is *Quercus ilex* L. These fruits are very abundant in the north of Algeria. Arrived at the laboratory, the samples underwent a manual sorting to rid the inappropriate fruits, then a washing with ordinary water to remove all kinds of impurities. The stones (edible part) were separated from their envelopes manually using a knife and reduced to small fragments (about 2×2×2 mm).

### 3.2. Thin layer drying experiment

Oven drying method AOAC [11] was used for determine the initial moisture content: 50 g of the fruits were oven dried at 105 °C during 6 h. An electronic balance (KERNALS 220-4N), with sensitivity ± 0.0001 g, was used to take the initial and final weight of the simple and the moisture content ($W$, %, db) was calculated using the equation (4) [9].

$$W,\% = \frac{M_0 - M_s}{M_s}100 \qquad (4)$$

where $M_0$ and $M_s$, respectively, is the weight (g) of simple and dried simple.

The initial moisture content of the *acorns* was 53.61% (db) while the final moisture content of dried simple was approximately 3% (db).

The drying kinetic curve was determined by following the mass losses of the fresh product during drying. A mass of 50 g of sample reduced to small particles (approximately 2×2×2 mm) was spread out in a thin layer on a perforated aluminium support and placed in an oven equipped with an aeration system and set at the defined temperature. Three oven temperatures were tested: 60, 70 and 80 °C. The samples were placed in the oven after at least 15 min of stable drying conditions. The weight measurements were carried out constantly at previously fixed time intervals. Drying is continued until the weight did not change significantly between three weighing successions. The mass evolution of the product during the drying was determined on the basis of successive weightings over time; thus, the moisture content at each instant was calculated using the equation (4).

### 3.3. Modelling of moisture ration

The experimental moisture content data were converted into moisture ration ($W_r$) according the following equation (5) [12].

$$W_r = W_t / W_0 \qquad (5)$$

where $W_0$ is the initial moisture content and $W_t$ is the moisture content at the instant $t$ (%, db).

The curves of moisture ration ($W_r$) against time ($t$) at the different drying temperatures were plotted. The literature proposes many mathematical models to represent the drying kinetics. In order to describe the drying behaviour of *acorns*, six mathematical equations listed in Table 1 were tested.

**Table 4.** Models tested to describe thin-layer drying curves of *acorns*

| Model name | Nonlinear regression$^{(*)}$ | References |
|---|---|---|
| Lewis | $W_r = \exp(-K_1.t)$ | [13] |
| Henderson and Pabis | $W_r = a.\exp(-K_2.t)$ | [14] |
| Logarithmic | $W_r = a.\exp(-K_3.t) + c$ | [15] |
| Thomson | $t = a.(\ln(W_r))^2 + b.\ln(W_r)$ | [16] |
| Wang and Singh | $W_r = a.t^2 + b.t + 1$ | [17] |
| Parabolic | $W_r = a.t^2 + b.t + c$ | [18] |

$^{(*)}$ $W_r$ moisture ration; $K_1$, $K_2$ and $K_3$= constants; a, b and c = coefficients.

### 3.4. Modelling approach of drying kinetic

In order to modelling the evolution of moisture content as a function of time during the drying of *acorns*, two models are proposed:

#### 3.4.1. Modelling with the First-Order kinetic model

The evolution of the moisture content during drying can be described by analogy with the thermal destruction of microorganisms or the inactivation of enzymes which follow a First-Order kinetic law (FO) shown by the equation (6) [8]:

$$dW/dt = -KW \qquad (6)$$

$K$: initial moisture reduction rate (or drying rate), in % min$^{-1}$.

The integration of this equation between initial moisture content ($W_0$) and final moisture content ($W$) and, on the other hand, between $t_0$ and $t$ gives:

$$\ln(W) = \ln(W_0) - K.t \qquad (7)$$

This indicates that the plot of ln($W$) versus the time ($t$) is a straight line and the slope is ($-K$). The nonlinear form is therefore exponential as indicated by the following expression (8):

$$W = W_0 e^{-Kt} \tag{8}$$

The regression of these forms (linear or nonlinear) can be verified practically using the coefficient of determination ($R^2$).

### 3.4.2. Modelling with the Pseudo-First-Order kinetic model

The Pseudo-First-Order (PFO) model is a mathematical equation that is used to describe the kinetics of the chemical substances adsorption on supports called 'adsorbents'. The evolution of the adsorbed quantity as a function of time is a function expressing the progressive increase of this one until a final stage showing the equilibrium between the solid/liquid phases and can be described by the Pseudo-First-Order law [19]. The equations (9) and (10) show the nonlinear and linear forms respectively of PFO model.

$$q_t = q_e - q_e e^{-kt} \tag{9}$$

$$\ln(q_e - q_t) = \ln(q_e) - K.t \tag{10}$$

$q_e$ and $q_t$ are the quantities of adsorption, respectively at equilibrium and at time $t$, $K$ is the adsorption rate (mg g$^{-1}$ min$^{-1}$). $q_e$ represents the maximum value removed by adsorption, while the smallest value is $q_0$ which represents the quantity adsorbed at $t_0$; $q_0$ is null for that it does not appear in the formula. For the drying process, since it is about a reduction of moisture, the maximum value is the initial content moisture ($W_0$), and the equilibrium moisture content ($W_e$) is the smallest value. The model, in this case, can be adapted to following:

$$\ln(W_t - W_e) = \ln(W_0 - W_e) - K.t \tag{11}$$

It is a straight line which can be verified experimentally using the coefficient of determination ($R^2$). The nonlinear form is:

$$W_t = (W_0 - W_e).e^{-Kt} + W_e \tag{12}$$

The extreme conditions (initial and at equilibrium) of the kinetics experiment satisfy this equation perfectly, giving reasonable results prescribed by the theoretical logic of the curve.

### 3.5. Reliability estimation of drying kinetic models

The reliability of the thin-layer drying kinetic models to experimental data was evaluated using the coefficient of determination ($R^2$), root mean square error (*RMSE*) and the sum mean of square error ($\chi^2$). The selection of the most adequate model was based on the highest value of $R^2$ and the lowest values of *RMSE* and $\chi^2$. Regression analyses were conducted with aid of Origin 8.0, the graphs are given by Excel (2010) software. The values of $R^2$ were given directly using the software, while the relatives errors were calculated according the equations (13) and (14).

$$RMSE = \sqrt{(1/N)\sum_{i=1}^{N}(W_{pre,i} - W_{\exp,i})} \qquad (13)$$

$$\chi^2 = \left[\sum_{i=1}^{N}\left(W_{\exp,i} - W_{pre,i}\right)^2\right] \Big/ (N-n) \qquad (14)$$

where $W_{exp,i}$ and $W_{pre,i}$ are the *i*th experimental and predicated values of moisture, respectively; *N* is the number of observations and *n* is the number of parameters.

### 3.6. Effective diffusivity and activation energy of thin layer drying of *acorns*

Effective moisture diffusivity was obtained from the slop of plotting of ln($W_r$) against drying time (*t*) using the equation (15) [1].

$$\ln(W_r) = \ln\left(8/\pi^2\right) - \left(\pi^2 D_{eff} / 4L^2\right).t \qquad (15)$$

where $W_r$ is the moisture ration, $D_{eff}$ is the effective moisture diffusivity (m²/s) and $L^2$ is the half-thickness (m) of the simple particles.

From the slop ($E_a/R$) of the straight line which may be given by the plot of ln($D_{\text{eff}}$) against the reverse of the absolute temperature (60, 70 and 80 °C), the activation energy was calculated, according to the Arrhenius relation (16) [20]:

$$\ln\left(D_{eff}\right) = \ln\left(D_0\right) - \left(E_a / RT_{abs}\right) \qquad (16)$$

where $D_0$ is the Arrhenius coefficient (m²/s), Ea is the activation energy (KJ $\text{mol}^{-1}$ $\text{K}^{-1}$), *R* is the universal gas constant (8.314 J $\text{K}^{-1}$ $\text{mol}^{-1}$) and $T_{abs}$ is the absolute temperature (K).

## 4. CONCLUSION

The thin layer drying behaviour of *acorns* was investigated at three oven temperatures (60, 70 and 80 °C). It was concluded that the experimental curves were characterised by an absence of the constant rate drying period and the drying time ranged from 60 to 150 min. Among the six models tested, Logarithmic model was the most adequate to describe the thin layer drying kinetics presenting the highest value of the coefficient of determination ($R^2 > 0.9896$) and the lowest values of the root mean square error ($RMSE < 0.514$ ) and the sum mean of square error ($\chi^2 < 0.0033$). In the range of temperatures tested, the effective moisture diffusivity increased from $4.016\times10^{-8}$ to $1.244\times10^{-7}$ m² s$^{-1}$.

The good fit ($R^2 > 0.9942$; RMSE < 2.238 and $\chi^2 < 6.014$) shown by FO and PFO models revealed their aptitude in the description of drying kinetic of *acorns* and predict the moisture content evolution as a function of time, and indicating the elimination of water from *acorns* was characterised by a *D-value* varying according the temperature from 25.8 to 69.78 min and a *Z-value* of about 20 °C.

The elimination of water from the *acorns* requires an $E_a$ of about 55 kJ mol$^{-1}$.

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