Moisture diffusivity of medicinal and aromatic plants during convective drying by hot air: Myrtle leaves.

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Abstract— In order to investigate the influence of the drying air characteristics on the drying performance of Tunisian myrtle leaves, drying tests were carried out on a tunnel dryer at the Laboratory of Energetic and Thermal and Mass Transfers LETTM. The sorption isotherm was determined at five temperature levels 40, 45, 50, 55, and 60 °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 with the most used empirical mathematical models available in the literature. The Peleg model was reported to be a suitable fit for the sorption experimental data in the mentioned investigated ranges of water activities and temperature. The myrtle leaves drying experiments were carried out at the five air temperatures in the range of 40-60°C air velocity of 2.0 m/s and performed at a relative humidity of 20%. Results indicated that drying took place in the falling rate period. Moisture transfer from myrtle leaves was described by applying Fick's diffusion model. The drying characteristic curve has 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 $1.266 * 10^{-10}$ to $13.06 * 10^{-10}$ m²/s in the temperature range of 40-60 °C and the relative humidity of 20%. An Arrhenius relation with an activation energy value of 104.63 kJ/mol was obtained.

Keywords: Drying kinetics, Sorption isotherms, Mass diffusivity, Myrtle leaves, Activation Energy.

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1. INTRODUCTION

Aromatic and medicinal plants are good examples of the pesticide properties of plants as bio-control agents and bio-aggressors. They present odorous principles that may be used in perfumery, soap making, and pharmacy after transformation into perfumed distilled water.

Currently, and according to scientific progress, therapeutics have evolved a lot and use aromatic and medicinal plants as raw materials for medicine production [1], which requires an operation to have a dry material. Among the aromatic plants recommended as medicinal is the Myrtle (Myrtus Communis), which is a widely used seasonal plant. Myrtus Communis (often referred to as myrtle) is an aromatic member of the Mytaceae family that has long been widely cultivated as a traditional medicinal plant in Mediterranean countries. Myrtus Communis is an evergreen tree or shrub that may grow to be 1–2 m in height. Smooth, leathery, elliptical myrtle leaves have a glossy dark green top surface and a matt, lighter green underside. To keep this plant and make it available all year round, a preservation process such as convective drying is necessary.

Owing to its controllable conditions, convection drying is generally found in the most common industrial fields [2, 3]. Conventional air drying is the most often used dehydration operation in the food and chemical industry [4, 5, 6]. Air drying at 50-60 °C produced a better profile than air drying at 40° and 70 °C. Lower temperatures resulted in oxidative reactions and the creation of new compounds, whereas higher temperatures resulted in compound breakdown and loss. Furthermore, some research found that drying temperature has a substantial impact on the changes in essential oil concentrations and compositions in aromatic plants such as mint [7], tea [8], Laurrier Noble [9], lemon balm [10], thyme [11], and ginger [12]. This operation also has a positive effect on the yield of essential oils extracted from these plants and changes their chemical composition [9]. This process consists in separating a product from a liquid by vaporization, which is accompanied by coupled heat and mass transfers because, during the drying process, the water present in the product dissipates gradually in the surrounding air due to the action of two phenomena: evaporation of the water at the product's surface and diffusion of the water within the product from its heart to its surface [13].

In the literature, several studies are available for determining effective moisture diffusivity in agricultural products [13-15]. Many researchers have used second Fick's law to infer the distribution of moisture along a drying body, and many authors have used this law to deduce the moisture distribution along with a material that is being dried [16,17]. This law assumes that the liquid phase moves through the object during the drying process due to moisture gradients that occur when the object reaches the driest zone, which is usually the surface [18]. The effective mass diffusivity (D_{eff}) of the product reflects its inherent moisture mass transport properties, which include various parameters such as molecular diffusion, liquid diffusion, hydrodynamic flow, vapor diffusion and other mechanism of mass transport [15]. As a result, the study of the mass transfer phenomena is based on the assumption that the effective moisture diffusivity represents all parameters that influence the process rate, which governs the spatial distribution of internal moisture. It is necessary to address the physical parameters of the material before any attempt to characterize the drying behavior, such as moisture diffusivity. Although considerable research has been done on the drying of myrtle leaves, there is few information on the impact of this parameter on the drying behavior of the myrtle at medium temperatures, particularly on the drying kinetics. Essential myrtle oil extracted either from freshly harvested myrtle leaves or from semidried or dried leaves through the distillation process for industrial applications. Rahimi. M [19] addressed experimentally the effect of convective drying conditions on the yield of the essential oil of the leaves of Myrtle (Myrtus Communis) and also on their chemical composition. The drying process is done by a tunnel dryer at laboratory scale. She made the experimental study of the sorption isotherm of the leaves of Myrtus Communis in different temperature conditions. Determining of sorption moisture isotherm is needed for drying kinetics of myrtle to determine the equilibrium moisture content. The falling rate phase is controlled by moisture diffusion (liquid and/or vapor). The associated property of moisture diffusion is the effective diffusivity, as it represents several mechanisms of water transport inside the products, such as capillary migration, vapor diffusion, diffusion-sorption... [20].

Many studies on moisture diffusivity for several products are made in conventional drying processes. However, there is a lack of moisture diffusivity values for convective drying for myrtle leaves. Therefore, the purpose of this paper is to determine the effective moisture diffusivity in myrtle leaves (Myrtus Communis), as well as the activation energy with the knowledge of the drying mechanisms of myrtle under convective conditions.

2. THEORETICAL CONSIDERATION

2.1 Desorption isotherm

At a specific temperature, the sorption isotherm determines the equilibrium concentration of water from the solid to the ambient moisture content. Many interactions between the solid structure and the water molecules occur at the microscopic level, which characterizes it. The explanation of the hygroscopic solid behavior is made possible by this curve. Depending on whether the sample is subjected to rising (water intake) or decreasing (water loss) humidity, we may estimate adsorption and desorption isotherms. Sorption isotherms define the water distribution quantity, and lowest water content that may be achieved at the end of the drying process [20].

$$X_{eq} = \frac{M_f - M_s}{M_s} \tag{1}$$

Solutions	**T (°C)**				
salts	**40**	**45**	**50**	**55**	**60**
KOH	0,062	0,061	0,057	0,056	0,055
LiCl	0,112	0,114	0,111	0,111	0,111
MgCl2	0,325	0,312	0,305	0,3	0,292
K2CO3	0,431	0,429	0,427	0,425	0,421
NaBr	0,514	0,513	0,512	0,489	0,441
NaNO3	0,589	0,589	0,588	0,572	0,56
NaCl	0,721	0,72	0,718	0,71	0,703
KCl	0,778	0,778	0,777	0,76	0,751
BaCl2	0,891	0,89	0,889	0,88	0,872

TABLE. 1. Standard values of the water activities $aw$for nine saturated salt solutions.

The desorption isotherms of myrtle leaves (Myrtus Communis) were determined, at five temperatures, using the static gravimetric method where moisture regulation is ensured by contact with aqueous salt solutions above which the water vapor pressure, at a particular temperature is completely defined. Various saturated salt solutions are prepared (Table.1) and the range obtained allows water contents to be obtained over the entire humidity range. The saline solutions are prepared in hermetically sealed jars and are kept isothermal in a temperature-controlled oven. In an oven at 105°C, moisture content was measured using the gravimetric technique until a constant mass was achieved ($\approx 24 hours$). The fresh product has a mean water content of $54 \pm 5\%$. (Dry basis). Many empirical correlations are available in the scientific literature for modeling desorption curves. These models include: (BET, Oswin, GAB, Henderson, Peleg). The table.2 lists the many models.

Model Name	**Equations**
BET	$Xeq = \frac{a.b.aw}{(1-\text{aw})(1+(b-1)aw)}$
Oswin	$Xeq = a\left(\frac{aw}{1-aw}\right)^b$
GAB	$Xeq = \frac{a.b.c.aw}{(1-\text{c.aw})(1-\text{c.aw}+\text{c.b.aw})}$
Henderson	$Xeq = \left(-\frac{\ln(1-aw)}{a}\right)^{\frac{1}{b}}$
Peleg	$Xeq = a(aw^c) + b(aw^d)$

TABLE. 2 The models applied to experimental data of desorption isotherms of myrtle leaves

2.2 CCS Drying Characteristic Curve

The drying characteristic curve CCS is defined by a normalized drying rate curve that combines the different curves of the moisture content evolution, which is valid for all operating conditions [19]. Models have been developed that can be used to analyze the drying process of a variety of products and air conditions using only a few laboratory drying experiments. It is determined as a function of the reduced moisture content by plotting the normalized drying rate against the drying rate in the first period (Van Meel, 1958).

$$XR = \frac{X - X_{eq}}{X_{cr} - X_{eq}} \tag{2}$$

$$f = \frac{\left(\frac{dX}{dt}\right)_t}{\left(\frac{dX}{dt}\right)_i} \tag{3}$$

In agricultural products, determining the critical moisture content X_{cr} and the drying rate $-\left(\frac{dX}{dt}\right)_0$ during the first phase is difficult. The short period where the drying rate is maximized, and it is often considered the first period because the drying period at a constant rate is not clear from our product. This last transformation allows all kinetics to be grouped together on the same graph, known as the drying characteristic curve CCS, as shown in Fig. 4.

$$XR = \frac{X - X_{eq}}{X_0 - X_{eq}} \tag{4}$$

$$f = \frac{\left(\frac{dX}{dt}\right)_t}{\left(\frac{dX}{dt}\right)_0} \tag{5}$$

Thus, employing of the typical drying curve, a single normalized drying rate curve may be used to depict the drying rate curves of a given product collected under various air conditions. This curve can be used to extrapolate data from myrtle leaf drying kinetics in convection dryer.

2.3 Mathematical modeling

The reduced moisture content XR of myrtle leaves in the drying experiments is given by Eq. (2). Assuming that the movement of moisture is one-dimensional, that the value of the moisture diffusion coefficient is constant and that the myrtle leaves samples are considered to be a homogeneous layer. For the one-dimensional case in cartesian coordinates, the fick's second law of diffusion [18] Eq. (6) can be used to describe the drying behavior of myrtle leaves.

$$\frac{\partial X}{\partial t} = D_{eff} \frac{\partial^2 X}{\partial^2 z} \tag{6}$$

This equation was used with one-dimensional moisture movement without volume change, constant diffusivity, uniform moisture distribution and negligible external resistance as assumptions. The equation has the following solution proposed by Crank (1975) in the case of a plane geometry:

$$XR = \frac{X - X_{eq}}{X_0 - X_{eq}} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left(-\frac{(2n+1)^2 * \pi^2 * D_{eff}}{e^2}(t)\right) \tag{7}$$

The Eq. (7) can be simplified by taking only the first term of the sum, so Eq. (7) can be expressed as:

$$XR = \frac{X - X_{eq}}{X_0 - X_{eq}} = \frac{8}{\pi^2} exp\left(-\frac{\pi^2 * D_{eff}}{e^2}(t)\right) \tag{8}$$

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

$$\ln(XR) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 * D_{eff}}{e^2}(t) \tag{9}$$

In the case of convective drying of myrtle leaves, we assume that the equilibrium moisture content on the surface will be zero. Where, it is shown in the literature that hides can be totally dried when convection is used [21]. As a result, $X_{eq} = 0$ will be assumed in this situation. The diffusivity can be determined using Eq. (9) by plotting the logarithm of the normalized drying curve as a function of time. The slope of this curve is proportional to the diffusivity, as indicated by Eq. (10).

$$La\ pente = -\frac{\pi^2 * D_{eff}}{e^2} \tag{10}$$

The estimated effective moisture diffusivity from drying data represents an overall mass transport property of moisture in the material which may include liquid and vapor diffusion, vaporization, condensation, and other possible mass transfer mechanisms [21]. The variation of the moisture diffusivity with moisture content, however, may be quite complex, especially in porous products. Effective diffusivity can be related to the variation of temperature by Arrhenius expression Eq. (11).

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (11)$$

Where D_0 is the diffusion factor (m²/ s), E_a is the activation energy (kJ/mol), T is the temperature of the drying air (K), R is the perfect gas constant 8.314 (J/mol K). Eq. (11) can be linearized in logarithmic form as follows [21]:

$$\ln\left(D_{eff}\right) = \ln\left(D_0\right) - \frac{E_a}{RT} \quad (12)$$

E_a and D_0can be determined by plotting $\ln\left(D_{eff}\right)$ as a function of $\frac{1}{T}$.

3. DRYING PROCEDURE

The drying unit used is a climatic blower, with a horizontal grate, and closed-loop, available at the Laboratory of Energetic and Thermal and Massive Transfers at the Faculty of Sciences of Tunis Fig. 1. It allows the control of temperature, relative humidity, and drying air velocity most commonly used in convective drying processes for low and medium temperatures. The airflow is produced by a centrifugal fan, passing through heating resistors to maintain its temperature rise. The relative humidity of the air is provided by a steam generator [20].

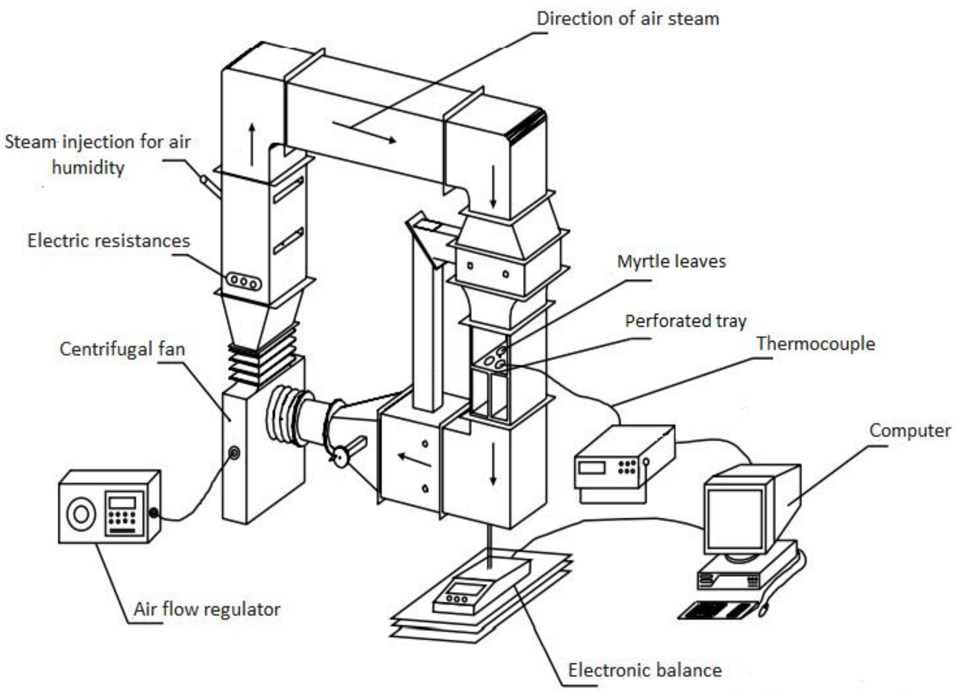

Fig.1 Schematic diagram of the drying loop for measurement of parameters of Myrtle leaves [16].

The air is circulated by a centrifuge ventilator, which passes through heating resistances to keep the temperature up. A vapor generator ensures that the relative humidity of the air is maintained. When you get to the test vein, the temperature and relative humidity are automatically controlled by a programmable logic controller (PLC) connected to a sensitive sensor controlled by a computer. With the help of a speed variator, the evaporation rate may be controlled. A condenser placed directly in front of the test vein condenses the water contained in the flow. The air returns to the fan through a seal, thus ensuring that the heating energy is saved. The loss of mass of the product is monitored over time by continuous weighing, using a digital balance of ±0.001 g accuracy (Mettler Toledo), placed outside of the dryer and connected to data acquisition and processing system, allowing the recording of the evolution of the mass of the product at regular times.

The samples are exposed to hot drying air that is directed vertically. This form of flow has the advantage of providing ideal conditions for air-product contact, as well as a high heat transfer coefficient (Fig. 1). During the drying process in the climatic blower, the loss weight of the samples was measured at a 5 min interval. We used samples of Tunisian myrtle leaves, placed on a perforated grate. The drying air conditions were kept constant.

All myrtle leaf samples were provided by the technicians of the Tunisian research center: “Institut National de Recherches en Génie Rural, Eaux et Forêts (INRGREF)” the thickness of the samples was $5 * 10^{-3}$m. The initial mass of the samples was about 20 g and the initial dry moisture content was 1.22 to 1.24 (kg H2O/kg dry matter). The tests were carried out at five different temperatures: 40, 45, 50, 55, and 60 °C, with velocity of 2 m/s and air humidity of 20%. A microcomputer recorded the drying process while continuously measuring the mass of the product at constant time intervals.

4. RESULTS AND DISCUSSION

4.1 Desorption isotherm

The hygroscopic equilibrium is reached after 20 days for myrtle leaves. The experimental curves obtained show that for the same water activity, the equilibrium water content increases with decreasing temperature (Fig.1) which is in agreement with other results presented in the literature [19]. To model these isotherms, the semi-empirical models mentioned in Table 2 were reviewed in order to identify the optimal model that best fits the desorption isotherms for myrtle leaves. The correlation coefficient (R^2) and the average of squared deviations between experimental and calculated data χ^2 are the criteria used, to choose the best equation that best fits the experimental desorption isotherms [20]. The larger R^2 values and the smaller χ^2 values, the better the fitting quality [24], the sorption isotherms were modeled using a variety of relationships [19, 20, 24, 29]. In our case, we put the GAB model, the BET model, the Peleg model, the Oswin model and the Henderson model to the test to see which one was most suited to the myrtle's behavior. Table 3 provides the coefficients of these models as well as the comparison criteria. The mathematical treatment was carried out utilizing the software 'Curve Expert 1.4' and a nonlinear regression analysis. The mathematical expressions for these two parameters are as follows:

$$\chi^2 = 1 - \frac{\sum_{i=1}^{n} (XR_{i,exp} - XR_{i,pre})^2}{N - z} \tag{13}$$

$$R^2 = \frac{\sum_{i=1}^{n} (XR_{i,exp} - XR_{i,pre})^2}{\sum_{i=1}^{n} (\overline{XR}_{i,exp} - XR_{i,pre})^2} \tag{14}$$

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

$$\overline{XR}_{i,exp} = \frac{1}{N} \sum_{i=1}^{n} XR_{i,exp} \tag{15}$$

Models	Temperature T° (C)	R^2	χ^2	Parameters
GAB	**40°C**	0,99572445	0,01226743	a=29,1416 b=0,0068 c=0,9262
	45°C	0,99688411	0,01328964	a=6,700 b=0,1516 c=0,84828
	50°C	0,99563491	0,00962815	a=1,136 b=0,09599 c=0,8923
	55°C	0,99427161	0,00894643	a=1,4471 b=0,10028 c=0,8817
	60°C	0,99551844	0,00907091	a=1,2151 b=0,1306 c=0,8613
BET	**40°C**	0,99572414	0,01124034	a=-1,1105 b=0,1955
	45°C	0,99612411	0,01224043	a=0,5691 b=0,1864
	50°C	0,9942211	0,01024012	a=-0,9566 b=0,3682
	55°C	0,99612454	0,01367023	a=-0,2737 b=0,4328
	60°C	0,99665453	0,01224066	a=0,1448 b=0,4940
Oswin	**40°C**	0,99183083	0,01643265	a=0,2464 b=0,3505
	45°C	0,9943452	0,00868064	a= 0,1285 b= 0,6442
	50°C	0,99434113	0,01085242	a=0,2159 b=0,6409
	55°C	0,9955252	0,00872987	a= 0,0673 b= 0,7906
	60°C	0,9962352	0,01160064	a=0,1968 b=0,3336
Henderson	**40°C**	0,96901327	0,03550864	a=8,4669 b=1,8429
	45°C	0,98093667	0,01772093	a=11,8891 b=2,0210
	50°C	0,96804788	0,01325971	a=15,7776 b=2,1010
	55°C	0,97993667	0,01892099	a=16,0211 b=2,1203
	60°C	0,97893667	0,01222087	a=16,9291 b=2,0898
Peleg	**40°C**	**0,99718012**	**0,00943538**	**a=0,1502 b=0,4738 c=0,7090 d=6,0073**
	45°C	**0,99816591**	**0,00740291**	**a=0,3229 b=0,2478 c=5,8315 d=0,3978**
	50°C	**0,99801884**	**0,00754293**	**a=0,2703 b=0,3366 c=0,4902 d=4,1300**
	55°C	**0,99780591**	**0,00817456**	**a=0,4882 b=4,9157 c=0,0567 d=0,5214**
	60°C	**0,99886547**	**0,00964059**	**a=0,0603 b=0,6816 c=0,4509 d=5,7064**

TABLE. 3 Results of the fitting statistics of various models at different drying temperatures

In order to depict the sorption isotherms behavior of myrtle leaves in the water activity range of 0.058-0.89and the temperature range of 40-60 °C, the Peleg model was chosen. The experimental desorption isotherm curves of Myrtus Communis leaves are presented in Fig. 2

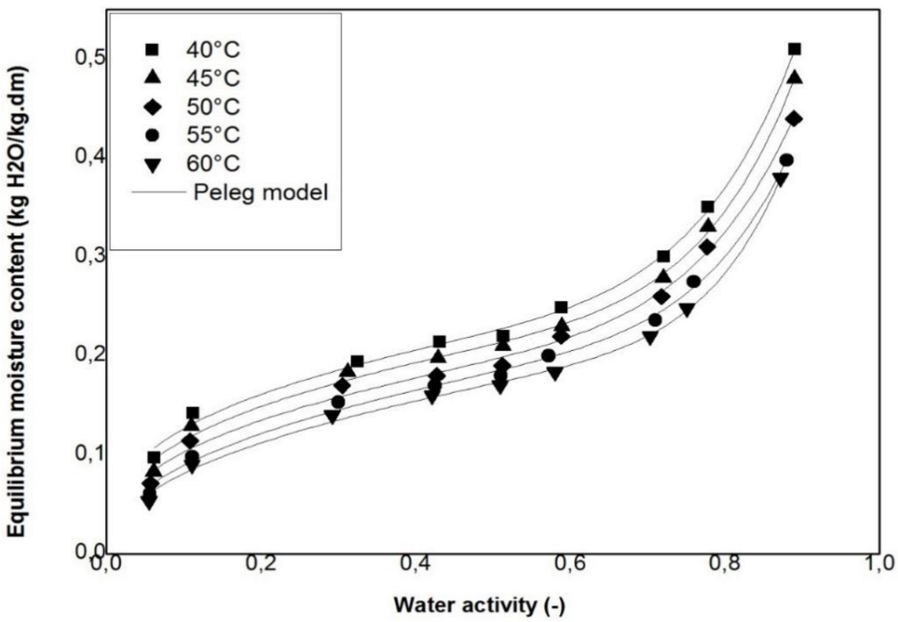

Fig. 2 Experimental and predicted (Peleg) sorption isotherms of myrtle leaf

On desorption isotherms, a considerable temperature influence was observed, as shown in the sorption curves (Fig. 2). The equilibrium moisture content increased with rising water activity at constant temperature, whereas the equilibrium moisture content increased with decreasing temperature at constant water activity. Temperature and water activity, generally, have considerable impacts on experimental equilibrium moisture content values. Similar results have been reported in a number of other studies, including different foods. [26, 27, 28, 30, 31, 13].

4.2 Drying curves

The drying curves of all drying tests conducted are reported in Fig. 3. In these figures, the moisture ratio MR was plotted versus time, for different values of air temperature and for the air velocity value kept constant. The device used to record the mass of the sample over time and the temporal evolution of the sample temperature. We will use the results of tests for different temperatures, all performed at the same velocity and relative humidity. The time-normalized drying curves are presented in Fig. 3 for various temperatures at 2 m/s air velocity. These curves also confirm that the effect of drying air velocity on the acceleration of the drying process is less important than that of temperature. Thus, the temperature is considered to be the main factor controlling the drying rate as mentioned in many studies [19, 23, 24]. Drying for the decreasing rate phase is controlled by the diffusion of water into the solid. This is a complex mechanism involving water in both the vapor and liquid states, which is very often characterized by effective diffusivity. The drying air temperature has a large influence on the drying process, so as the air temperature rises, the water content of the leaves decreases.

This effect is caused by the heat input to the product, which increases as the air temperature rises. As a result, the rate of water diffusion in the product increases with temperature.

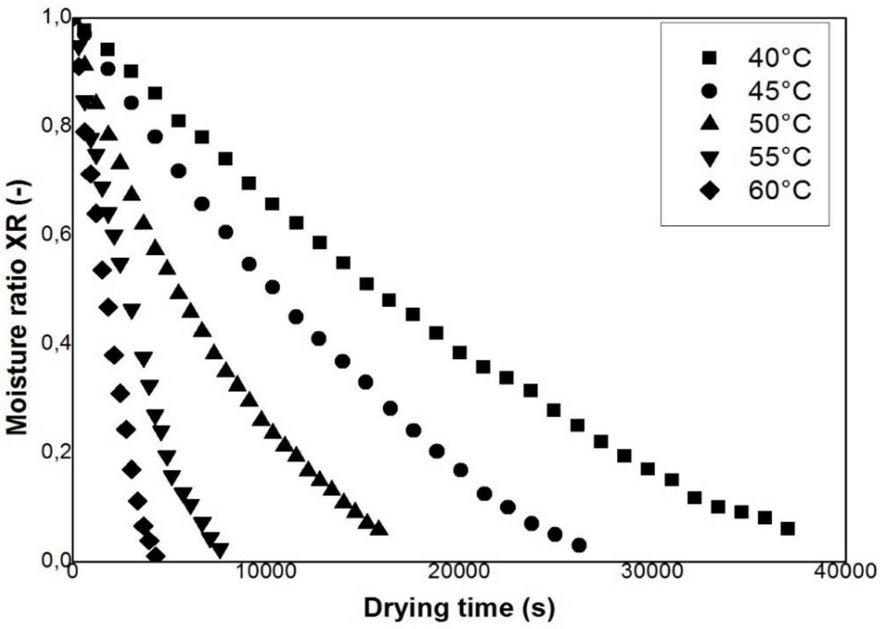

Fig. 3 Evolution of the moisture ratios of myrtle leaves over time

4.3 Characteristic Drying Curve

The characteristic equation of the drying rate of Myrtle leaves (Myrtus Communis) was obtained with "Origin 6.0" program by smoothing the experimental points with a polynomial function of degree 3 (R^2 =0.998):

$$f = 0.01475 + 0.92622 * X + 0.13525 * X^2 - 0.03814 * X^3 \quad (16)$$

The rate of drying is highest in the first stage and then gradually decreases with time. This is due to the low internal moisture resistance of the material at the start of the drying process. These results correspond to the findings of several other researchers [13, 14, 16, 21]. This finding provides information about the gradual increase in internal resistance to heat and mass displacement. Thus, diffusion of water into the solid is the most plausible physical mechanism that dominates the moisture movement of myrtle samples.

As a result, a high temperature necessitates a large amount of exertion for heat transfer, and it also rates up the drying process because the temperature provides a large difference in vapor pressure (Hertz Knudsen's law). The difference between partial pressure and saturated vapor pressure of water in the air decreases as the temperature rises, which is one of the main forces for drying.

In addition, the amount of water released at the beginning is very significant, as the rate of water removal is high during this phase. During the drying process, the free water is quickly removed from the product. Thus, in the final stages, the water is hardly removed, which will make the drying process slow. For this reason, the air temperature is recognized as the main parameter influencing the air drying of products.

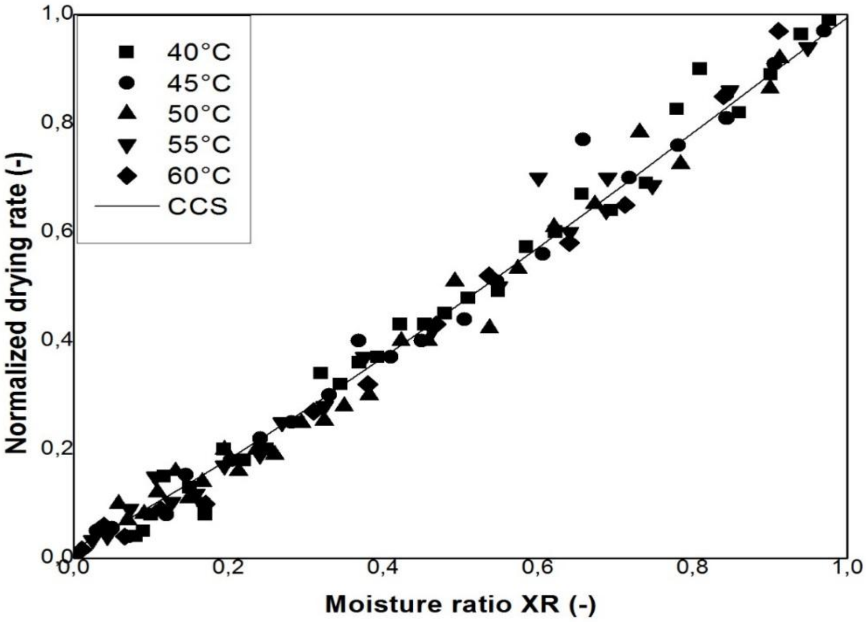

Fig. 4 Drying characteristic curve of myrtle leaves obtained for different drying experiments

4.4 Effective moisture diffusivity

Data obtained from the drying operations were used to calculate the effective moisture diffusivity D_{eff} in myrtle leaves (Myrtus Communis). The curves typically showed a consistent diffusion-controlled drying behavior under all operating conditions. In addition, a significant influence of air temperature on drying could be observed in these curves. As shown in Fig. 5, the drying time decreases significantly as the drying temperature increases [25]. The effect of temperature on the effective moisture diffusivities has been illustrated in the table 4.

There are no published data on effective moisture diffusivities D_{eff} for moisture transfer during drying of myrtle leaves. As a result, we used the Ln (XR) versus time curves, as shown in Eq. (9) to extract the values of the effective moisture diffusivities in the myrtle samples during the drying process for five airflow temperatures (40, 45, 50, 55, and 60 °C). According to an Arrhenius-type law, the coefficient D_0 increases with air temperature, where the activation energy E_a is a parameter to be adjusted, assuming that the activation energy is constant. This should be due to the high energy transfer of the airflow when the temperature is increased. The pore volume increases with temperature [26], which could also help the removal of water molecules [25]. Fig. 5 shows normalized drying curves fitted to linear functions that minimize quadratic mean error. Moisture diffusion theory can explain the driving mechanism in the falling drying rate period in convection drying of myrtle leaves, based on the excellent agreement between fitted lines and curves.

Eq. (12) of Arrhenius-type described the effect of temperature on effective diffusivity. This corresponds to the relationships described in the literature [13, 18]. The effective diffusivities presented in this study are within the range of other products mentioned diffusivities of 10^{-8}

to 10^{-11} m²/s [33, 34]. The average D_{eff} values for myrtle in our study ranged between $1.266*10^{-10}$ and $13.06*10^{-10}$ m²/s.

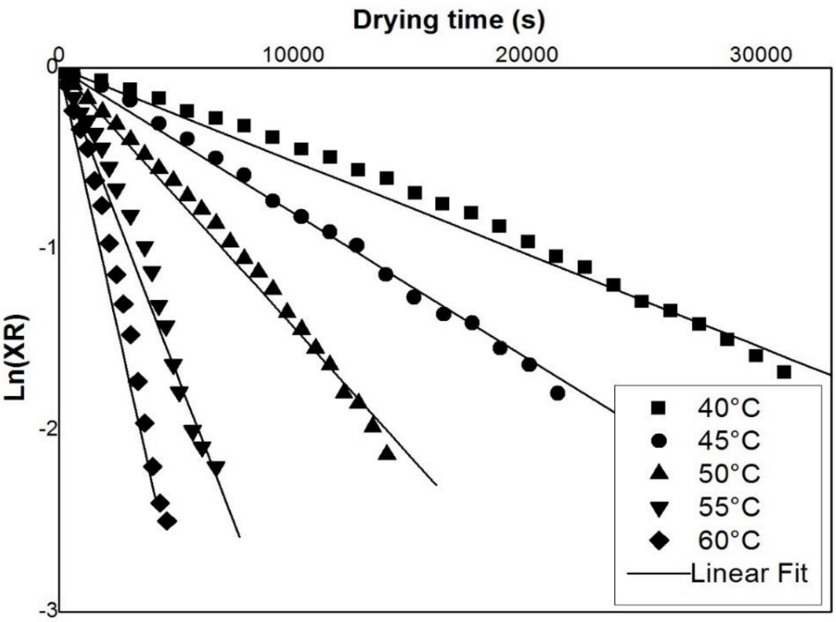

Fig. 5 Variation of logarithm of myrtle leaves moisture ratio with drying time for five air drying temperature, 40, 45, 50, 55, and 60°C, at constant relative humidity RH = 20%.

T(°C)	**40**	**45**	**50**	**55**	**60**
D_{eff} **(×10⁻¹⁰ m²/s)**	1,266	2,052	3,57	8,121	13,06
E_a **(kJ/mol)**		104,63			
D_0 **(×10⁻² m²/s)**		5,1			
X_0		0,545			

TABLE. 4 Values of diffusivity, apparent activation energy E_a and diffusion factor D_0 at different airflow temperatures

Eq. (17) describes the influence of temperature on effective diffusivity of myrtle leaves. The linear fitting of $Ln(D_{eff})$ versus $\frac{1}{T}$ is represented by this Arrhenius-type equation. This accords to the correlations described in the literature [13, 15, 27].

$R^2 = 0.995$ indicates a strong correlation between coefficients and experimental data, which is a very acceptable result. From the linear regression relationship in Eq. (17), deduced from a fitting Fig. 6, and by identification with Eq. (12) we obtain the diffusion activation energy of water in myrtle leaves $E_a = 104{,}63$ kJ /mol, and diffusion factor $D_0 = 5{,}1 \times 10^{-2}$ m²/s. The activation energy value is of the same order as the values obtained in bioproducts drying processes [13, 29]. Therefore, it was confirmed that the effective diffusivity coefficient in myrtle leaf samples depends on the drying air temperature with an Arrhenius-type exponential function.

$$\mathrm{Ln}(\mathrm{D_{eff}}) = 17{,}334 - 12584{,}9\frac{1}{\mathrm{T}} \tag{17}$$

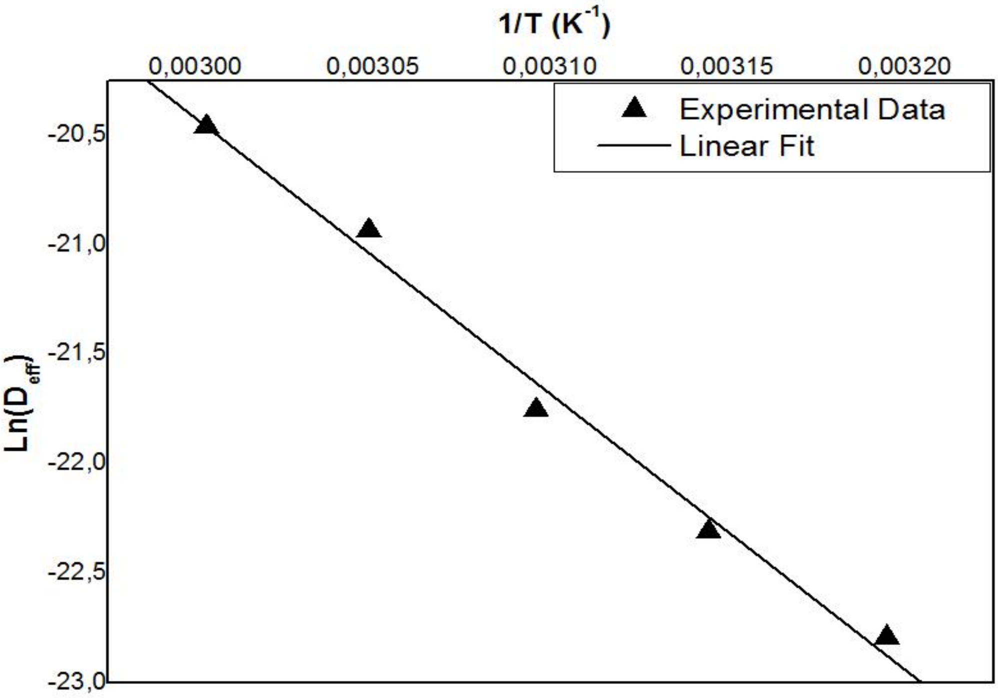

Fig. 6 Arrhenius-type relationship between effective diffusivity and temperature for myrtle leaves

The experimental results of effective diffusivities for various convective drying temperatures are shown in Fig. 7. The fitting function used in these studies was an exponential function that was mostly dependent on the airflow temperature, as indicated in Eq. (18). The results are always in accord with those achieved by other similar products [31, 32, 33].
The expression for the effective moisture diffusivity, as a function of temperature, obtained from the fitting of the experimental data is given by Eq (18):

$$\mathrm{D_{eff}} = 0{,}01123 \exp(\mathrm{T}/8{,}479) * 10^{-10} \tag{18}$$

The findings reveal that the moisture diffusivity of myrtle leaves during convective drying is proportional to the temperature of the drying air, meaning that as the air temperature rises, the moisture diffusivity rises as well, owing to the additional energy received by the internal water.
As a result, as the quantity of energy consumed in the process grows, water evaporation increases, coupled with a high degree of humidity mobility, affecting diffusivity [30]. Moreover, using convective energy throughout the drying process with airflow temperatures up to 60 °C enhanced drying rates without affecting the final quality of products.
In terms of drying parameters, Table 5 shows the values of the activation energy for various products, including myrtle leaves from our study and other similar products from the literature. The order of magnitude between our results and those found in the literature [29, 33, 34] is consistent.

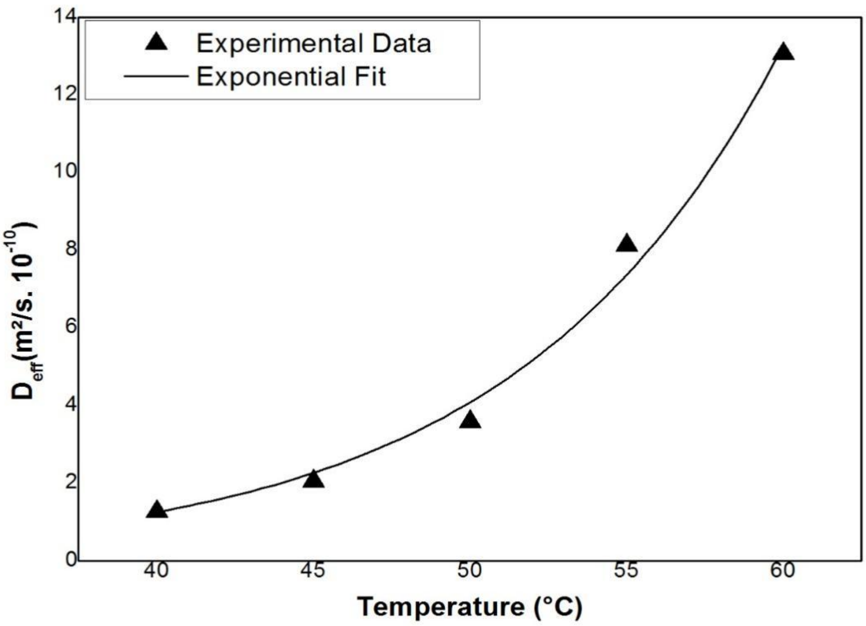

Fig. 7 Diffusion coefficients for convective drying at several airflow temperatures of myrtle leaves.

Product	**Activation Energy**	**References**
MyrtusCommunis	104,63	Present work
Mint	82,93	Park et al, [7]
Black tea	406,02	Panchariya et al [8]
Laurus Nobilis	36,48	I, Doymaz [9]

TABLE. 5 Activation energy values for different similar products**.**

CONCLUSION

The current study is about the drying kinetics of myrtle leaves in a convective dryer under the influence of five different drying air temperatures (40, 45, 50, 55, and 60 °C). The static gravimetric method was used to determine the sorption isotherm of myrtle leaves. For various drying air temperatures, the effective moisture diffusivity of myrtle leaves was determined experimentally. The estimated effective moisture diffusivities fall within a typical range reported in the literature for drying of similar products. The experimental results show that only the drying phase participates in the drying process at a falling rate, which is due to the absence of free water in such products. Moreover, the experimental results indicate that the drying rate increases with the rise of the drying air temperature while the drying time falls. The experimental studies evaluated the effective moisture diffusivity of myrtle leaves and for different air-drying temperatures, the results show that the effective moisture diffusivity increases from $1.266 * 10^{-10}$ to $13.06 * 10^{-10}$ m²/s for an increase in temperature from 40 to 60 °C, while the activation energy remains fixed at $104.63\ \mathrm{kJ/mol}$. Effective diffusivities increase with temperature following the Arrhenius-type relationship. Although results described in the present study were applied to myrtle leaf samples, the conclusions can be extended to materials with similar drying characteristics, such as mint.

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Nomenclature

S : Surface	m²
t : Time	s
t_C : Critical time	s
T :Temprature	°C
D_{eff} : Effective moisture diffusivity	m²/s
D_0 : Pre-exponential factor	m²/s
E_a : Activation energy	KJ/kg
R : Universal gas constant	KJ/mol. K
e : Sample thickness	m
X : Moisture content of sample at time t	kg H2O/kg dry matter
X_0 : Initial moisture content	kg H2O/kg dry matter
X_e : Equilibrium water content dry basis	kg H2O/kg dry matter
XR : Dimensionless moisture content	kg H2O/kg dry matter
Aw : Water activity	-
HR : Relative air humidity	%

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