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Experimental Determination and Modeling of the Drying Curves of *Eucalyptus camaldulensis*

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Abstract

The medicinal and aromatic plants have a great importance for both the pharmaceutical industry and the traditional medicine in Tunisia. This plants contain high moisture content. Such moisture could cause their deterioration in storage. Drying is an interesting solution to keep the quality of these products.

This paper presents the thin layer convective drying and mathematical modeling of *Eucalyptus camaldulensis*. For these purposes, a forced convection dryer consisting of drying tunnel is a controlled atmosphere that we have equipped with the appropriate measuring instruments. This is a wind tunnel where we can control the temperature, velocity of the drying air.

To determine the kinetic parameters, the drying data were fitted to various models. Among the models proposed, the semi-empirical Page model has shown a better fit to the experimental drying data.

Keywords: Isotherms; Adsorption; Desorption; Drying; Modelisation

Introduction

The aromatic and medicinal plants are more used for several applications in pharmacy, medicine and food processing therefore the necessity of their preservation. *Eucalyptus camaldulensis* is usually used for medicine for several aims such as anti-inflammatory of the respiratory tract [1,2].

In addition, *Eucalyptus camaldulensis* oil is an important, most popular and widely used essential oil. In order to preserve this seasonal plant, and make it available to consumers during the whole year, it undergoes specific technological treatments, such as drying.

The leaves are perishable in nature because of high moisture content. For the effective utilization of the leaves, the postharvest processing aspect is important so that the quality of the leaves can be preserved with enhanced shelf life. Dehydration is a useful method of preserving the leaves; it enhances the resistance of high humid products against degradation by decreasing their water activity. Conventional air drying is the most frequently used dehydration operation in food and chemical industry due to its controllable conditions and less dependency on climatic conditions. However, studies on the drying characteristics of *Eucalyptus camaldulensis* leaves are scarce in the literature [2].

The drying kinetics of food is a complex phenomenon and requires dependable models to predict drying behavior. There are several studies describing the drying behavior of various fruits, vegetables and medicinal and medicinal plants. The aim of this research was to observe the effect of air drying temperature and velocity on the drying time and to fit the experimental data to four thin-layer drying models and estimate the constants.

Material and Methods

Determination of adsorption-desorption isotherms

Determination of adsorption-desorption isotherms sorption isotherms are essential tools in dehydration processes for predicting shelf-life stability, packaging and drying of a desired product. The moisture sorption isotherm describes the relationship between the water activity (a_w) and the equilibrium moisture content (X_e) of a product at a constant pressure and temperature. Thus, with knowledge of the moisture sorption isotherm, it is possible to predict the maximum moisture that *Eucalyptus camaldulensis* leaves can be allowed to gain or lose during storage or drying. The desorption isotherms data are useful in the drying analysis while the adsorption isotherms data can be used for establishing a storage method [1].

The objective of this study is the determination of curves of adsorption and desorption of a variety of *Eucalyptus camaldulensis*, for different values of the temperature. The Vapor Sorption Dynamics is a gravimetric technique for the study of interactions of vapors with solids. It can accurately determine sorption isotherms at different temperatures (20-50°C) and to a range of preset relative humidity (RH) values.

The apparatus we used is a Dynamic Vapor Sorption. The experimental apparatus is shown in Figure 1. It consists of a sample kept in a temperature controlled chamber, a microbalance, to measure the absorption and desorption of the sample vapor a flow of carrier gas, with controlled vapor content. Often, this is generated by mixing a flow with a flow dry saturated steam.

Modeling of the adsorption desorption isotherms

Numerous models have been suggested in the literature to describe the relationship between equilibrium moisture, water activity and temperature have been developed. The goodness of fit of each model was evaluated using performance parameters for nonlinear models, such as mean relative percent error, coefficient of determination [2].

Drying kinetics of *Eucalyptus camaldulensis* equipment

The main objective of the present work is to determine drying kinetics of one of the *Eucalyptus camaldulensis*. This kinetics is studied

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in a laboratory drying tunnel where the product is put in thick-layer under controlled air conditions. The undertaken experiments consist of studying the separated influence of drying air velocity on the drying rate.

Description of experimental apparatus

The different experiments undertaken consist of studying the drying kinetics of *Eucalyptus camaldulensis* in a drying tunnel working by forced convection under controlled atmosphere. The experimental apparatus is supplied with instruments measuring drying air velocity, temperature of drying and air moisture content. Three tests were performed at each of the drying air velocity. The experimental apparatus (Figure 1) is a laboratory drying tunnel, which provides an air flow with controlled characteristics.

Modeling of the drying curves

In order to determine the moisture content as function of drying time, a large number of models have been proposed in the literature for the drying curves (Tables 1 and 2). The moisture content of the *Eucalyptus camaldulensis* leaves was calculated using the following equation:

$$MR = \frac{M_t - M_e}{M_o - M_e}$$

Where MR is the moisture content M_t is the moisture content at a specific time (g water/g dry base), M_0 is the initial moisture content (g water/g dry base), M_e is the equilibrium moisture content (g water/g dry base).

Where, a, b, c, k, k_0, k_1 and n are drying constants in the models.

Results and Discussion

Adsorption-desorption isotherms

Figures 1-3 illustrate adsorption (Red line) desorption (blue line) isotherms of *Eucalyptus camaldulensis* leaves obtained at various water activity for three temperatures levels of 25, 35 and 45°C.

The results resemble the characteristic sigmoid shape of the type II pattern isotherm according to Brunauer's classification, which is frequently found for biological and food materials [5]. The figures also show the effect of hysteresis between adsorption and desorption over almost the entire range of water activity at the three temperatures, in which water content on the desorption isotherm is higher than that on the adsorption side at the same water activity. One of the reasons for differences in moisture content between the two closure points is

Model	Equation
Langmuir	$X_e = \frac{A.B.Hr}{1+Hr}$
BET	$X_e = \frac{(A+B.T)C.Hr}{(1-Hr)(1-Hr+C.Hr)}$
GAB	$X_e = \frac{(A.B.C.Hr}{(1-BHr)(1-1-C)BHr)}$
Chung-Pfost	$A_w = \exp[\frac{-A}{T+B}.\exp(-C.X_e)]$
Peleg	$X_e = A.Hr^{k1}.Hr^{k2}$
Smith	$X_e = A - B.Ln(1-Hr)$
Oswin	$X_e = (A+B.T).\left[\frac{Hr}{1-Hr}\right]^C$
Henderson	$1-Hr = \exp(-A(T+B).X_e^C$

Table 1: Thin layer drying models given by various authors for drying curves [3].

Figure 2: Schematic representation of the laboratory drying tunnel.

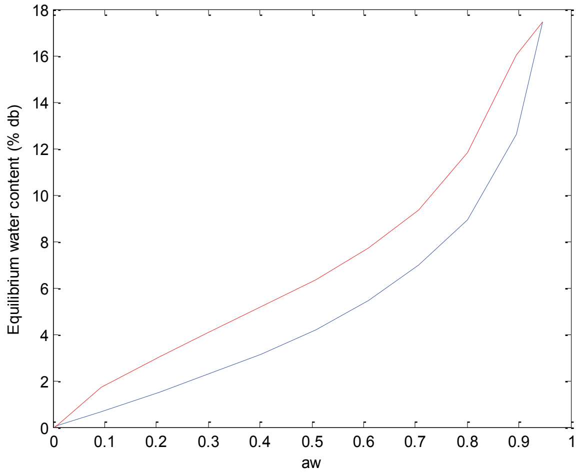

Figure 3: Adsorption desorption isotherms at 25°C.

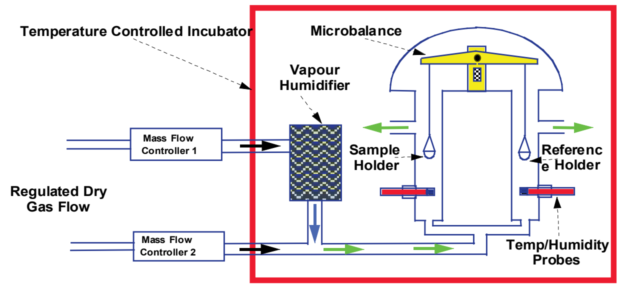

Figure 1: Schematic representation of the DVS.

that, during drying (desorption), some solutes may supersaturate below their crystallization water activity and thus hold more water as water activity is lowered especially for products with high sugar content [6].

There is also a decrease in the equilibrium moisture content with increasing temperature, at a constant water activity; this can be explained by the change in the excess enthalpy of water binding, dissociation of water, or increase in solubility of solute in water as temperature increases. Similar trends for many medicinal plants have been reported [7].

Modeling of the adsorption desorption isotherms

The results of regression analysis of fitting the sorption equations to experimental data of *Eucalyptus camaldulensis* at three temperatures are presented in Table 3. The observed and predicted sorption isotherms using the different models are shown in Figures 4-6. The GAB equation provided the best fit to experimental data of adsorption and desorption isotherms with the maximum R^2**.**

Drying kinetics of *Eucalyptus camaldulensis*

Effect of the velocity: In order to study the influence of drying air velocity on drying kinetics of *Eucalyptus camaldulensis*, we vary the air velocity from 1.5 to 3 $m.s^{-1}$. Figure 7 represents the variation of the *Eucalyptus camaldulensis* water content as function of time for different drying air velocity. We note that an increase in the air velocity results an increase in the moisture content.

Effect of the temperature: Figure 8 presents the drying curves of *Eucalyptus camaldulensis* at different temperatures. We note that an increase in the temperature results an increase in the moisture content. There is, consequently, reduction of the time of drying. Experimental and GAB predicted adsorption isotherms at 25°C.

We observe the absence of phase with increasing pace (phase I) and with constant pace (phase II) and the presence of phase III (with decreasing pace) in the curves of drying. The absence of phase I is due to the difficulty of the capillary migration of water from the heart to the wet rigid surfaces of leaves, which requires a significant heat input to vaporize the water in the within the seed and the discharging in the vapor state.

Similar results were obtained for various aromatic and medicinal plants [8-11]. It is apparent from Figure 8 that increasing the drying temperature caused a significant decrease in the drying time.

Model fitting of drying curves

Four drying models have been used to describe drying curves. The statistical parameters used to evaluate the goodness of fit of the models were the coefficient of determination R^2 and the reduced chi-square χ^2. The values of constants, R^2 and standard error for different drying conditions determined by nonlinear regression analysis are presented in Table 3.

The best model that can be used to describe the drying behavior of *Eucalyptus camaldulensis* is selected based on the highest R^2 and lowest χ^2 values. The results of statistical analysis for the models are shown in Table 3. The R^2 values varied from 0.493 to 0.998 while the χ^2 varied from 1.214 10^{-5} to 2.9 10^{-3}, for all drying temperature.

Model	Equation
Newton	MR= exp (-kt)
Page	MR= exp ($-kt^n$)
Henderson and Pabis	MR=a exp (-kt)
Logarithmique	MR= a exp (-kt) + c
Verna et al.	MR=a exp (-kt) + (1-a) exp ($-k_0$ t)
Two-term	MR= a exp ($-k_0$t) + b exp ($-k_1$t)

Table 2: Mathematical models used to describe the drying kinetic [4].

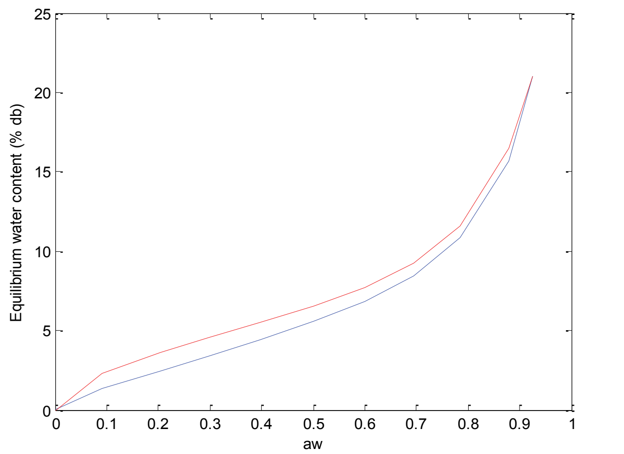

Figure 4: Adsorption desorption isotherms at 35°C.

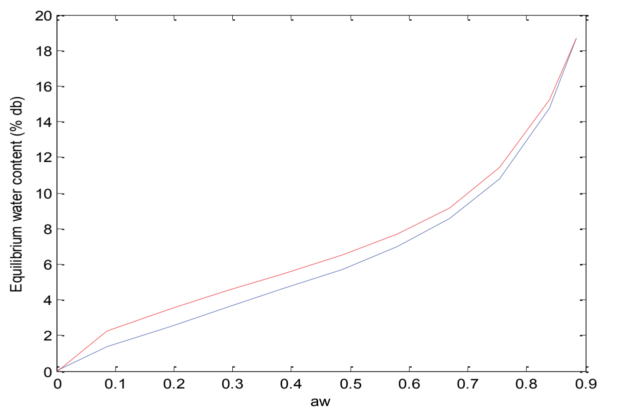

Figure 5: Adsorption desorption isotherms at 45°C.

Conclusion

Varieties of *Eucalyptus camaldulensis* drying experiments are performed in a tunnel dryer to investigate the effects of velocity of air on the drying kinetics of leaves. The second experimental part to determine the equilibrium moisture by using a method of dynamic vapor sorption DVS. According to the drying curves, the mere presence of phase 2 is noted. Thus, among the studied statistical models, the logarithmic model showed good correlation with the experimental curves of drying with an R^2 of 0.993 and a $\chi 2$ of 3.415610 to 5.

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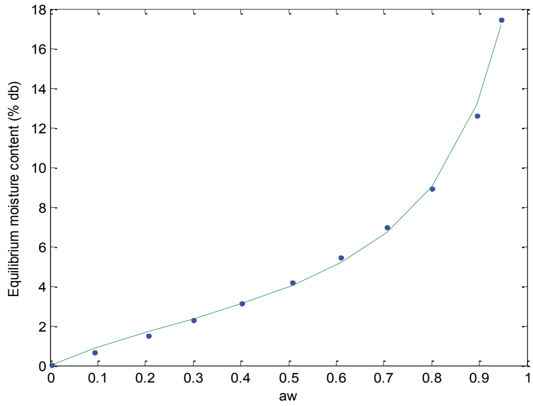
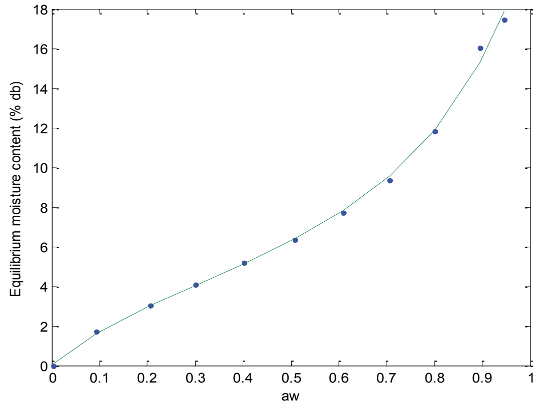
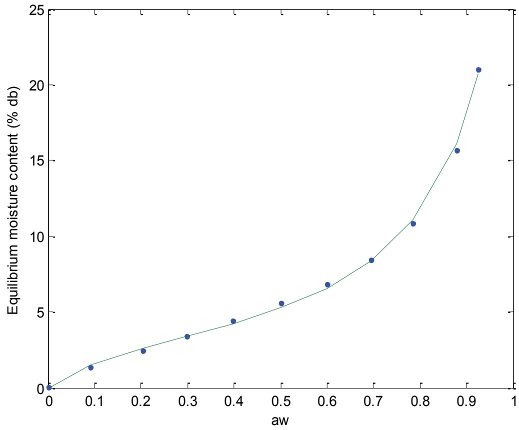
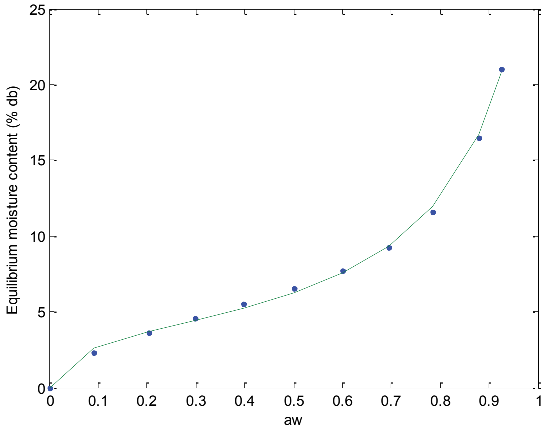


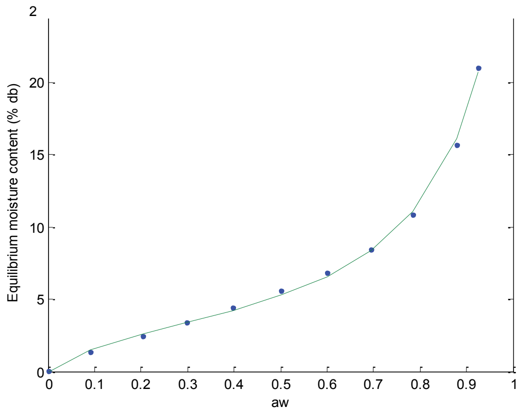




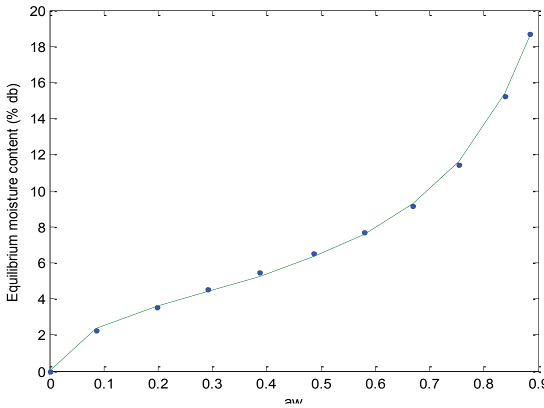
Experimental and GAB predicted adsorption isotherms at 35°C.



Experimental and GAB predicted desorption isotherms at 35°C.



Experimental and GAB predicted adsorption isotherms at 45°C.



Experimental and GAB predicted desorption isotherms at 45°C.

Figure 6: Comparison of experimental and predicted adsorption desorption equilibrium moisture contents at different temperatures.

Model	Constants				
	T=30°C	T=40°C	T=50°C	T=60°C	T=70°C
Henderson et Pabis	a=1.123 k=0.009 R^2=0.869 χ^2 =8.86 10^{-4}	a=1.149 k=0.012 R^2=0.964 χ^2 =13 10^{-4}	a=0.968 k=0.014 R^2 =0.998 χ^2 =1.51 10^{-5}	a=0.708 k =0.025 R^2 =0.7056 χ^2 =2.2 10^{-5}	a= 0.666 k= 0.028 $R^{2=}$0.807 $\chi^{2=}$1.214 10^{-5}
Newton	k=0.008 R^2 =0.878 χ^2 =6.393 10^{-4}	k=0.009 $R^{2=}$0.948 χ^2=1.3 10^{-4}	k=0.015 R^2 =0.997 χ^2=1.705 10^{-5}	k=0.036 R^2 =0.869 χ^2=6.241 10^{-4}	k=0.044 R^2 =0.564 χ^2 =3.429 10^{-4}
Page	k=0.029 n=0.7145 R^2=0.914 χ^2 =5.164 10^{-4}	k=0.026 n=0.7938 R^2 =0.948 χ^2 =1.300 10^{-4}	k=0.019 n=0.9433 R^2 =0.998 χ^2 =1.343 10^{-5}	k=0.127 n=0.652 R^2=0.831 χ^2=3.992 10^{-4}	k=0.135 n=0.674 R^2=0.493 χ^2=2.390 10^{-4}
Logarithmique	a =1.101 k =0.030 c =0.312 R^2=0.970 χ^2=2 10^{-4}	a =1.136 k =1.371 c =0.388 R^2 =0. 890 χ^2=2.9 10^{-3}	a=0.731 k=1.868 c=0.265 R^2 =0. 790 χ^2=2.3 10^{-3}	a =0.546 k =2.124 c =0.178 R^2 =0. 629 χ^2=1.7 10^{-3}	a =0.697 k =0.055 c =0.123 R^2 =0.813 χ^2=2.243 10^{-4}

Table 3: Statistics results obtained from the selected models in different temperature.

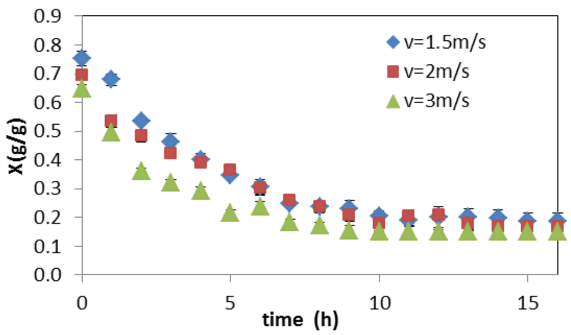


Figure 7: Influence of the drying air velocity on the evolution of water content as a function of time.

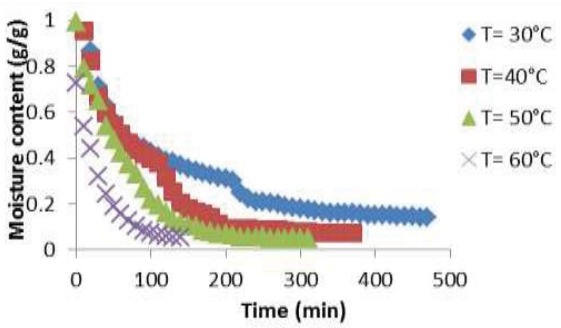


Figure 8: Variation of moisture ratio with drying time under different drying temperatures.

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