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Sorption Isotherms and Drying Characteristics of *Artemisia arborescens* Leaves

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Abstract: The water vapour sorption isotherms of *Ar. arborescens* leaves in the water activity range of 0.0572-0.8980 were determined at three temperatures 30, 40 and 50°C by the gravimetric static method. Five sorption models were fitted with the sorption data. The modified Oswin and GAB models were found to be the most suitable for describing the sorption curves. Solar drying experiments in thin layer were conducted in a forced convection solar dryer consisting of a solar air collector, an auxiliary heater and a drying cabinet. The experimental drying curves showed only the falling drying rate period. The main factor in controlling the drying rate was the temperature. The drying rate equation was determined empirically from the characteristic drying curve. Ten statistical models were tested for fitting the experimental drying curves. The Logarithmic model was found to be the most suitable for describing the drying curves of *Ar. arborescens* leaves.

Key words: *Artemisia arborescens*, convective drying, food storage, heat of sorption, solar energy, sorption isotherms

INTRODUCTION

Artemisia arborescens grows along the Mediterranean coast of European and African countries (Tutin *et al*., 1976). It is very used in Morocco as an infusion with the tea. In traditional medicine, *Ar. arborescens* leaves primary uses are to stimulate the body and has antifebrile, antiseptic, emmenagogue properties; it can also help against indigestion caused by gastralgia and in case of hepatic failure. It is taken in small doses and sipped; the intensely bitter taste plays an important part in its therapeutic effect. In China a local species is used in the treatment of malaria.

Phytochemical analysis of *Ar. arborescens* resulted in the isolation from the ethanolic extract of the known compounds: artemitin, arborescin, sesamin, (+) -lirioresinol beta-dimethyl ether, chrysoeriol, apigenin, β-sitosteryl glucoside, dihydroridentin and chrysoeriol 4-glucoside. (Abu Zarga *et al*., 1995; Alberto Marco *et al*., 1997; Grandolini *et al*., 1988).

Essential oils that contain chamazulene are important in therapeutic applications because of their apparent radical scavenging activity. Interesting research supporting this activity was carried out by Rekka *et al.* (1996), who investigated the role of chamazulene *in vitro* experiments using an iron (II)/ascorbate system to generate hydroxyl radicals inducing membrane lipid peroxidation in liver microsomes. Antiviral essays demonstrated that the liposomal incorporation of *Ar. arborescens* essential oil enhanced its *in vitro* antiherpetic activity (Sinico *et al*., 2005).

An important factor in the quality loss of dried medicinal plants during storage is the water activity (a_w) witch influences the biochemical reactions and stability of dried products. Some of these reactions are lipid oxidation, caking, agglomeration and degradation of vitamins and lycopene (Jamali *et al*., 2006a). A large number of models have been proposed in the literature for the sorption isotherms (Ait Mohamed *et al*., 2005a; Van den Berg and Bruin, 1981).

Drying is one of the methods of conserving agricultural products. The drying process can be conducted by using solar energy. Solar drying is a well known food preservation technique to reduce the moisture contents of medicinal plants, which prevents deterioration within a period of time regarded as the safe storage period. Generally, agricultural products are dried either naturally on paved ground under the sun or with a drying system. There are no works in the literature on the sorption isotherms and the drying process of *Artemisia arborescens* leaves.

This study was mainly concerned with the:

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- Determination of the equilibrium moisture sorption isotherms of *A. arborescens* leaves at 30, 40 and 50°C.
- Fitting of the experimental sorption isotherms with five empirical models and calculation of the net isosteric heat of sorption from experimental data.
- Determination of the effect of drying air temperature and air flow rate on the drying kinetics of *Ar. arborescens* leaves.
- Fitting of the drying curves with ten mathematical models and determination of the Characteristic Drying Curve (CDC).
- Computation of the moisture effective diffusivity and the activation energy of *Ar. arborescens* leaves.

MATERIALS AND METHODS

Ar. arborescens leaves, whose initial moisture content is 2.9558 (kg water/kg dm) and used for the sorption and drying experiments, was grown in the region of Marrakech, Morocco and got from the local market in May 2006 (Fig. 1).

Sorption procedure: The sorption method used was the static gravimetric technique, which is based on the use of saturated salt solutions to maintain a fixed relative humidity when the equilibrium is reached. The water activity of the product is identical to the relative humidity of the atmosphere at equilibrium conditions and the mass transfer between the product and the ambient atmosphere is assured by natural diffusion of the water vapour. Six salts were chosen (KOH ($MgCl_2$, $6H_2O$), K_2CO_3, $NaNO_3$, KCl ($BaCl_2$, $2H_2O$)) so as to have a range of water activity of 0.0572-0.0898 (Ait Mohamed *et al*., 2005a). The experimental apparatus consisted of six glass jars of 1 L each with an insulted lid. Every glass jar was filled to quarter depth with a saturated salt solution (Fig. 2).

Duplicated samples each of 0.4 g (±0.0001 g) for desorption and 0.1 g (±0.0001) for adsorption were weighed and placed into the glass jars. The weight recording period was about three days. This procedure continued until the weight was constant. The equilibrium moisture content of each sample was determined in a drying oven at 105°C for 24 h. The hygroscopic equilibrium of *Ar. aborescens* leaves was reached in 11 days for desorption and 9 days for adsorption.

Drying procedure: The experimental set up, shown in Fig. 3, mainly consists of an indirect forced convection solar dryer with a solar air collector, an auxiliary heater, a circulation fan and a drying cabinet. It was described in detail in references (Ait Mohamed *et al*., 2005b; Kouhila *et al*., 2002; Lahsasni *et al*., 2004a).

Fresh *Ar. arborescens*

Dreid *Ar. arborescens*

Fig. 1: Fresh and dried *Ar. arborescens* leaves

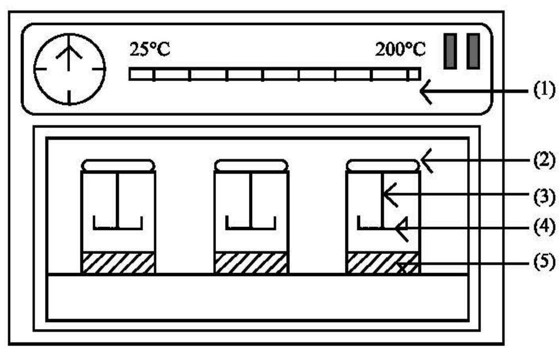

Fig. 2: Experimental apparatus for the sorption isotherms measurement (1) Thermostated bath, (2) Glass jar containing salt solution, (3) sample-holder, (4) Product and (5) Saturated salt solution

Experiments, conducted in May-June 2006, were performed to determine the effect of different drying air conditions on the drying kinetics. Three drying air temperatures (40, 50 and 60°C) and three drying air flow rates (0.028, 0.056 and 0.084 m^3 sec^{-1}) were selected to examine the influence of temperature and air flow rate on the drying kinetics of *Ar. arborescens* leaves.

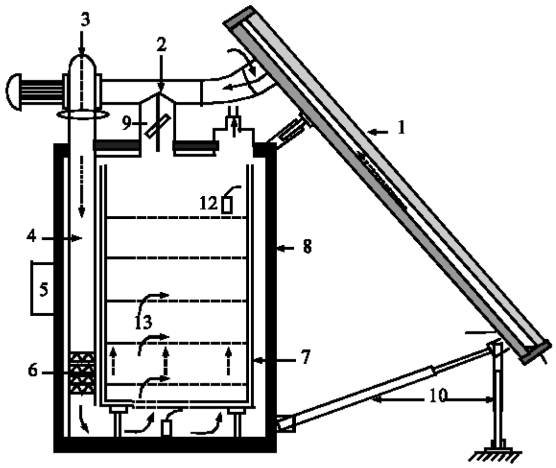

Fig. 3: Schematic diagram of the solar dryer, (1) solar collector, (2) circulation fan, (3) fan, (4) air flow direction; (5) control box, (6) auxiliary heating system, (7) shelves, (8) drying cabinet, (9) recycling air, (10) control foot, (11) exit of air, (12) humidity probes and (13) thermocouples

The mass of the product used in drying experiments was (20.0±0.01) g per tray. In the drying experiments, the 2nd and 10th shelves were not selected for efficient utilization of the drying air.

However, the samples were uniformly spread evenly on a drying tray that was then placed on the first shelf of the drying cabinet. The heated air enters the drying cabinet below the trays and flows upwards through the samples. In order to dry the product sufficiently, it was important to keep the drying air temperature constant. In solar drying processes, the drying air temperature can vary based on the magnitude of the solar radiation. However, the auxiliary heater was used for controlling the drying air temperature. The amounts of daily solar radiation were measured with a solarmeter. Temperature measurements and recordings at different points in the solar dryer were made by Cr-Alumel thermocouples (0.2 mm diameter) connected to a data logger enabling ±0.1°C accuracy and the outlet temperatures were measured with thermometers. The relative humidities were measured by capacitance sensors. These values were determined by probes Humicolor ±2% (Ait Mohamed *et al.*, 2005b; Kouhila *et al.*, 2002; Lahsasni *et al.*, 2004b). A digital weighing apparatus (±0.001 g) measures the mass loss of the product during the drying process. During each drying experiment, the weight of the product on the tray was measured by removing it from the drying cabinet for approximately 15-20 sec. These measurements were undertaken each 10 min at the beginning of the experiment and at 40 min intervals at the end. The initial and final moisture contents of each sample were determined by a drying oven whose temperature was fixed at 105°C for 24 h.

ANALYSIS OF DATA

Sorption isotherms of *Ar. arborescens*: Various models have been proposed and tested in the literature for correlating the equilibrium moisture content with water activity (Ait Mohamed *et al.*, 2005a; Jamali *et al.*, 2006b). Five models (Table 1) were selected for fitting the experimental data of sorption of *Ar. arborescens* leaves. Nonlinear regression analysis, using computer programs, was used to estimate the models constants from the experimental results of sorption isotherms.

The correlation coefficient (r) was one of the primary criteria for selecting the best equation describing the sorption curves of *Ar. arborescens* leaves. In addition to r, the various statistical parameters such as; reduced Mean Relative Error (MRE) as a percent and Standard Error of Estimate of moisture (SEE) were used to determine the quality of the fit (Chen and Morey, 1989). These statistical parameters can be calculated as follows:

$$MRE = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{Me_{i,exp} - Me_{i,pre}}{Me_{i,exp}}\right| \quad (1)$$

$$SEE = \sqrt{\frac{\sum_{i=1}^{N}\left(Mei_{,exp} - Mei_{,pre}\right)^2}{N-n}} \quad (2)$$

Where:

$Me_{i,exp}$ = The experimental equilibrium moisture content at observation I.

$Me_{i,pre}$ = The predicted equilibrium moisture content at this observation.

N = The number of observations.

n = Number of constants in models.

The net isosteric heat of sorption (Q_{st}) can be assessed at several water activities values using the Clausius-Clapeyron equation (Lopes *et al.*, 2002):

$$\frac{\partial \ln(a_w)}{\partial (T)} = \frac{Q_{st}}{RT^2} \quad (3)$$

Integrating Eq. 3, assuming that the net isosteric heat of sorption (Q_{st}) is temperature independent gives the following equation:

Table 1: Mathematical models applied to the sorption isotherms of *Ar. arborescens*

Model name	Model equation	Reference
Modified Henderson	$1-a_w=\exp\left[-A(\theta+B)M_e^{\ C}\right]$	Thompson *et al.* (1968)
Modified Chung-Pfost	$a_w=\exp\left[-\frac{A}{\theta+B}\exp(-CM_e)\right]$	Pfost *et al.* (1976)
Modified Oswin	$M_e=(A+B\theta)\left[\frac{a_w}{1-a_w}\right]^C$	Oswin (1946)
Modified Halsey	$a_w=\exp\left[\frac{-\exp(A+B\theta)}{M_e^{\ C}}\right]$	Iglesias and Chirife (1976)
GAB	$M_e=\frac{ABCa_w}{[1-Ba_w][1-Ba_w+BCa_w]}$ $B=B_0\exp\left(\frac{h_1}{RT}\right);C=C_0\exp\left(\frac{h_2}{RT}\right)$	Van den Berg and Bruin (1981)

$$\ln(a_w)=-\left(\frac{Q_{st}}{R}\right)\frac{1}{T}+K \qquad (4)$$

The Marquardt-Levenberg non-linear optimisation method (Kouhila *et al.*, 2002) was used to find the best equation for the *Ar. arborescens* leaves sorption isotherms.

Drying kinetics of *Ar. arborescens* leaves: Several authors (Belghit *et al.*, 2000; Bellegha *et al.*, 2002; Kouhila *et al.*, 2002; Lahsasni *et al.*, 2004b), based on the Van Meel (1958) transformation, have used simply the initial moisture content (M_0) and the equilibrium Moisture content (M_e) to obtain Moisture Ratio (MR) and initial drying rate $(-M/dt)_0$ to normalize the drying rate as follows:

$$MR=\frac{M-M_e}{M_0-M_e} \qquad (5)$$

$$f=\frac{\left(-\frac{dM}{dt}\right)_t}{\left(-\frac{dM}{dt}\right)_0} \qquad (6)$$

Where:
f = The dimensionless drying rate.
$(-dM/dt)_t$ = The drying rate at any time of drying (kg water/(kg dm min)).

The solar drying curves obtained were fitted with ten different thin-layer drying models (Table 2). The correlation coefficient (r), the reduced chi-square (χ^2) and the Mean Bias Error (MBE) were the statistical parameters used for selecting the best equation to describe the thin-layer drying curves of *Ar. arborescens* leaves. These parameters can be calculated as follows:

$$\chi^2=\frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N-n} \qquad (7)$$

$$MBE=\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i}-MR_{exp,i}\right) \qquad (8)$$

Where:
$Mr_{exp,i}$ = The ith experimental moisture ratio.
$Mr_{pre,i}$ = ith predicted moisture ratio, N the number of observations and
n = Number of constants in models.

In this study, the coefficients of each model, the most suitable model for drying of *Ar. arborescens* leaves, the relationship between the drying air temperature and the coefficients of the best suitable model were also determined.

The experimental results obtained have shown that internal mass transfer resistance due to presence of falling rate drying period controls drying time. The drying data in the falling rate period are usually analysed by Fick's diffusion equation. The solution of this equation and the form of Eq. 9 can be applicable for slab geometry by assuming uniform initial moisture distribution, constant diffusivity and negligible shrinkage:

$$MR=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2D_{eff}t}{4H^2}\right) \qquad (9)$$

Where:
D_{eff} = The effective moisture diffusivity ($m^2\ sec^{-1}$);
H = The half thickness of the slab in samples (H = 0.3 mm) and n is a positive integer constant. In practice, only the first term of Eq. 9 is used yielding:

$$MR=\frac{8}{\pi^2}\exp\left(-\frac{\pi^2D_{eff}t}{4H^2}\right) \qquad (10)$$

Table 2: Selected mathematical models applied to the drying curves

Model name	Model equation	References
Lewis	MR = exp(-kt)	Bruce (1985)
Page	MR = exp(-kt^n)	Doymaz (2007)
Modified page 1	MR = exp((-kt)^n)	Lahsasni *et al.* (2004a)
Modified page 2	MR = exp(-(kt)^n)	White *et al.* (1981)
Henderson and Pabis	MR = a exp (-kt)	Henderson and Pabis (1961)
Logarithmic	MR = a exp(-kt) + c	Togrul and Pehlivan (2003)
Two term	MR= a exp(-k_0t) + b exp(-k_1t)	Henderson (1974)
Two term exponential	MR = a exp(-kt) + (1-a) exp (-kat)	Sharaf-Elden *et al.* (1980)
Wang and Singh	MR = 1 + at + bt^2	Wang and Singh (1978)
Approximation of diffusion	MR = a exp(-kt) + (1-a) exp (-kbt)	Yaldiz *et al.* (2001)

Effective diffusivity is also typically calculated by using slope of Eq. 10, namely, when natural logarithm of MR versus time was plotted, straight line with a slope was obtained:

$$\text{Slope} = \frac{\pi^2 D_{eff}}{4H^2} \tag{11}$$

The correlation between the drying conditions and the determined values of the effective diffusivity can be expressed by using an Arrhenius type equation (Doymaz, 2007; Madamba *et al.*, 1996) such as:

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

Where:

D_0 = The pre-exponential factor of the Arrhenius equation (m^2 sec^{-1}),

E_a = The activation energy of the moisture diffusion (kJ mol^{-1}),

T = The air absolute temperature (K) and R is the universal gas constant (J mol^{-1} k^{-1})

RESULTS AND DISCUSSION

Water sorption isotherms

Experimental results: The experimental results of the equilibrium moisture content at 30, 40 and 50°C at six water activities are given in Table 3. As shown in this table, a significant temperature effect on the adsorption and desorption for the full range of water activities was observed for this product.

The equilibrium moisture content increases with decreasing temperature at constant water activity (Fig. 4). The sorption isotherms present the characteristic S-shaped curve, typical of sorption isotherms of many plants and food materials (Ait Mohamed *et al.*, 2005a; Kechaou and Maalej, 1999; Kouhila *et al.*, 2001; Lahsasni *et al.*, 2003). The hysteresis effect was distinctly observed in the range of temperatures tested (Fig. 5).

Fitting sorption models to equilibrium moisture data: The results of non linear regression analysis of fitting the adsorption and desorption equations to experimental data of *Ar. arborescens* leaves at three temperatures are presented in Table 4 and 5. For all the models tested, parameters A, B and C are found to be temperature dependent.

For desorption isotherms, modified Oswin model was found to be the best estimator for predicting the equilibrium moisture of the *Ar. arborescens* leaves. This model gives the highest r (0.9970), the lowest MRE (11.5196%) and the lowest SEE (2.1026) values. For adsorption isotherms, GAB model was found to be the best estimator for predicting the equilibrium moisture of *A. arborescens*. This model gives the highest r (0.9995), the lowest MRE (3.0554%) and the lowest SEE of (0.6763) values.

Isosteric heat of sorption: The net isosteric heat of sorption Q_{st} values are calculated from the equilibrium data at different temperatures using Eq. 4 and obtained at different moisture contents. The variation of the heats of sorption of *Ar. arborescens* leaves with equilibrium moisture content is shown in Fig. 6. The net isosteric heat of sorption decreases slightly with increasing moisture.

The net isosteric heat of desorption an adsorption of *Ar. arborescens* leaves can be expressed mathematically as a polynomial function of equilibrium moisture content:

$$Q_{st}\,(\text{desorption}) = 6.9071 - 0.2003\,M_e + 0.0034\,M_e^2 \quad (r = 0.9775)\ S_r = 0.1151 \tag{13}$$

$$Q_{st}\,(\text{adsorption}) = 3.2351 - 0.0223\,M_e - 0.0019\,M_e^2 \quad (r = 1)\ S_r = 0.0043 \tag{14}$$

Drying characteristics

Drying experiments: Nine drying experiments were conducted during the period of May-June 2006 in Marrakech. The solar collector provided energy at the rate of 15.500 kWh m^{-2} year^{-1} (Kouhila *et al.*, 2002). During the experiments, the daily solar radiation varied between 250 and 980 W m^{-2}; the ambient air temperature ranged

Table 3: Adsorption and desorption equilibrium moisture contents M_e (kg water kg^{-1} dm) of *Ar. arborescens* leaves obtained at different water activities and temperatures

30°C			40°C			50°C		
a_w	M_e (des)	M_e (ads)	a_w	M_e (des)	M_e (ads)	a_w	M_e (des)	M_e (ads)
0.0738	8.0645	5.2632	0.0626	7.0423	5.2632	0.0572	6.3492	5.2083
0.3238	12.6984	11.8280	0.3159	12.1622	9.5745	0.3054	9.8361	8.5106
0.4317	16.3934	12.7660	0.4230	15.0685	11.8280	0.4091	13.2353	11.8280
0.7275	37.0968	25.0000	0.7100	36.9231	24.1758	0.6904	27.6923	21.2766
0.8362	52.9412	35.9551	0.8232	48.2143	34.7826	0.8120	43.8596	31.9149
0.8980	63.4615	48.8636	0.8910	61.8182	46.1538	0.8823	59.7222	42.5532

Table 4: Estimated model coefficients (r), MRE and SEE of the five equations fitted to the desorption isotherms of *Ar. arborescens* leaves

	Modified henderson	Modified chung-pfost	Modified oswin	Modified halsey	GAB
A	0.0019	121.6443	9.9795	1.7259	13.1845
B	-27.1503	14.3843	0.1496	0.0345	
C	1.0921	0.0537	1.6324	1.3455	
B_0					3.2158
C_0					2925804.3725
h_1					-3325.0218
h_2					-33402.6127
r	0.9944	0.9769	0.9970	0.9915	0.9954
MRE (%)	14.0857	12.3892	11.5196	6.3508	12.3892
SEE	3.0178	6.3455	2.1026	1.8029	2.8476

Table 5: Estimated model coefficients (r) MRE and SEE of the five equations fitted to the adsorption isotherms of *Ar. arborescens* leaves

	Modified henderson	Modified chung-pfost	Modified oswin	Modified halsey	GAB
A	0.0023	125.4596	8.5079	2.2788	0.9232
B	-22.7039	14.4893	0.1627	0.0533	
C	1.0622	0.0746	1.8553	1.5677	
B_0					1.0540
C_0					121.8950
h_1					-338.2001
h_2					-4516.7762
r	0.9923	0.9726	0.9983	0.9990	0.9995
MRE (%)	15.7955	23.5700	7.7522	6.0925	3.0600
SEE	2.5746	4.9944	1.1921	0.9530	0.6763

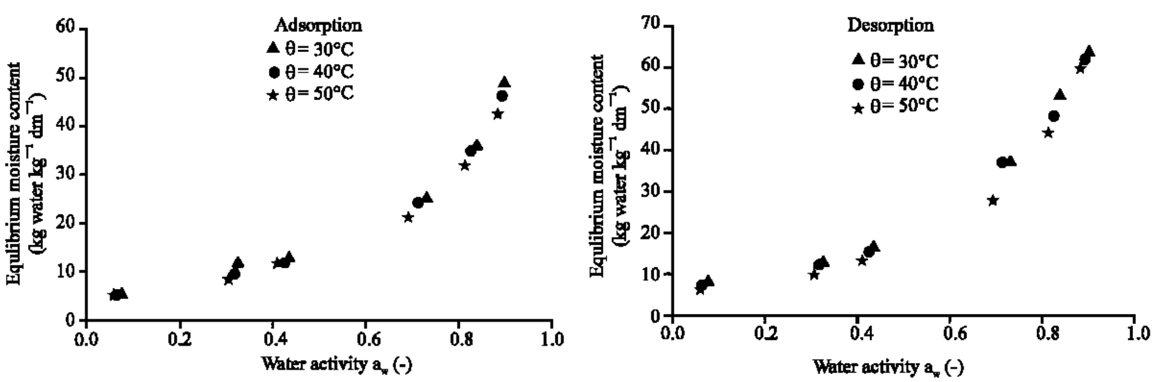

Fig. 4: Influence of temperature on the adsorption-desorption isotherms of *Ar. arborescens* leaves

from 27 to 41°C the ambient air Relative Humidity (Rh) ranged from 41 to 47.2%; the drying air temperature ranged from 32 to 38°C and the drying air flow rate ranged from 0.028 to 0.084 m^3 sec^{-1}. The initial moisture content of the *Ar. arborescens* ranged from 2.9558 to 5.1705% kg water per kg dry matter dm and was reduced to the final moisture content which varies from 0.1417 to 0.2893 kg water per kg dry matter (Table 6).

The drying air conditions have an important influence on the rates of these curves. At constant drying air flow rate (0.056 m^3 sec^{-1}), the changes in the drying rate versus moisture content are shown in Fig. 7. It is apparent that the drying rate decreases continuously with decreasing moisture content. The drying rate increases with the increase in the drying air temperature and the highest values of drying rate were obtained in experiment

Table 6: Drying conditions during experiments in the solar dryer

Experiment No.	Dv (m^3 sec^{-1})	θ±0.1 (°C)	Rh±2 (%)	M_e ±0.00025 (kg water kg^{-1} dm)	M_0 ± 0.045 (kg water kg^{-1} dm)	M_f ± 0.0021 (kg water kg^{-1} dm)	t (min)
1	0.028	40	42.0	0.1789	2.9558	0.1417	280
2	0.028	50	43.5	0.1844	3.4783	0.2893	175
3	0.028	60	47.2	0.1988	4.6747	0.1476	70
4	0.056	40	44.9	0.1897	3.1721	0.1620	240
5	0.056	50	41.0	0.1753	3.9929	0.1704	145
6	0.056	60	40.2	0.1724	5.0255	0.1660	60
7	0.084	40	45.0	0.1901	3.0912	0.1620	220
8	0.084	50	43.0	0.1825	4.2219	0.2368	145
9	0.084	60	41.0	0.1753	5.1705	0.1799	60

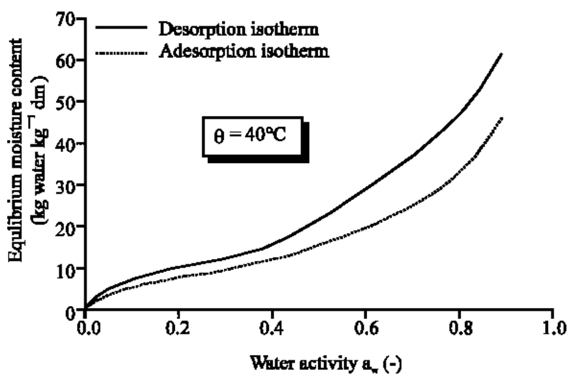

Fig. 5: Sorption hysteresis phenomenon of *Ar. arborescens* leaves

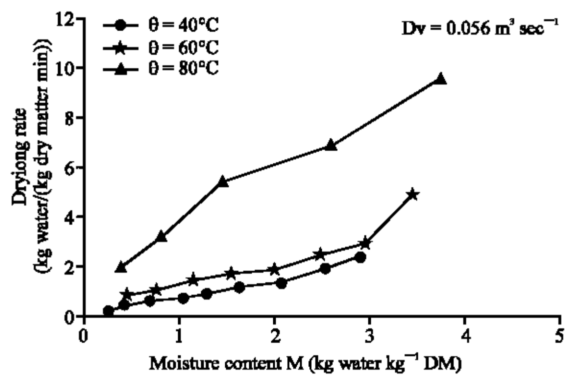

Fig. 7: Influence of drying air temperature on drying rate during drying of *Ar. arborescens* leaves

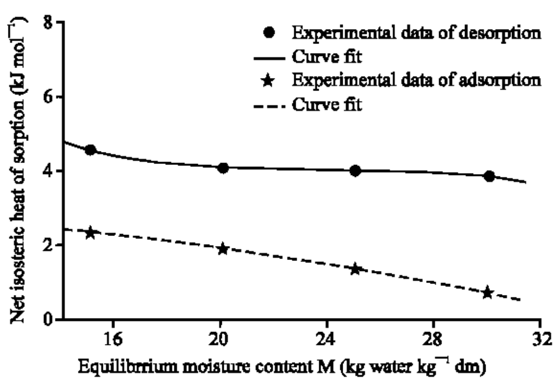

Fig. 6: Net isosteric heat of sorption for different moisture contents of *Ar. arborescens* leaves

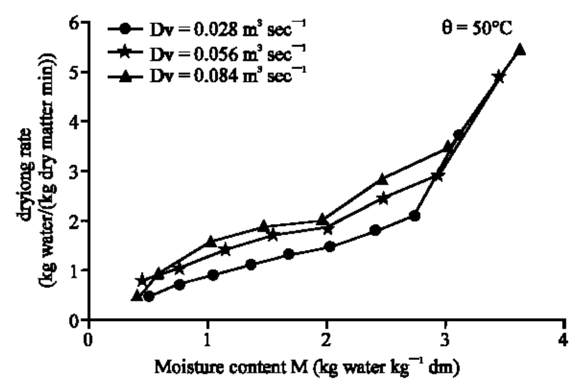

Fig. 8: Influence of drying air flow rate on drying rate during drying of *Ar. arborescens* leaves

six (θ = 60°C and D_v = 0.056 m^3 sec^{-1}). Similarly, at constant drying air temperature, the drying rate increased with the increase in drying air flow rate (Fig. 8).

Figure 7 and 8 describe that there is an absence of phase 0, the increasing drying rate period, where the temperature of the product is increased without any substantial loss of water and phase 1, the constant drying rate period. There is only the presence of the falling drying rate period (phase 2). These results are in agreement with the drying literature (Lahsasni *et al*., 2003; Lahsasni *et al*., 2004b; Yaldiz and Ertekin, 2001).

Characteristic drying curve: The Van Meel (1958) transformation is applied for determining the characteristic drying curve of *Ar. arborescens* (Kouhila *et al*., 2002). Experimental drying data are plotted in Fig. 9 to represent f = f (MR). This figure shows that all the drying curves obtained with the moisture ratio and the dimensionless drying rate, for the different tested conditions, fall into a tight band, indicating that the effect of variation in different conditions is small over the range tested. A polynomial model was found to fit best the dimensionless drying data of *Ar. arborescens*.

Table 7: Models constants and statistical results obtained from selected drying models

Model	Coefficients	r	χ^2	MBE
Lewis	k = 0.0128	0.9949	0.0010	0.0010
Page	k = 0.0067; n = 1.1470	0.9983	0.0004	0.0042
Modified page 1	k = 0.0208; n = 0.6147	0.9949	0.0011	0.0010
Modified page 2	k = 0.0127; n = 1.1470	0.9983	0.0004	0.0042
Henderson and pabis	a = 1.0514; k = 0.0136	0.9966	0.0007	0.0051
Logarithmic	a = 1.1348; k = 0.0104; c = -0.1229	0.9996	9.2073×10^{-5}	4.1120×10^{-6}
Two term	a = 0.8257; k_0 = 0.0136;			
	b = 0.2257; k_1 = 0.0136	0.9966	0.0010	0.0051
Two term exponential	a = 1.6609; k = 0.0168	0.9984	0.0003	0.0036
Wang and singh	a =-0.0098; b = 2.4931×10^{-5}	0.9984	0.0608	0.0770
Approximation of diffusion	a = 6.5530; k = 0.0069; b = 0.8893	0.9996	9.7783×10^{-5}	-0.0003

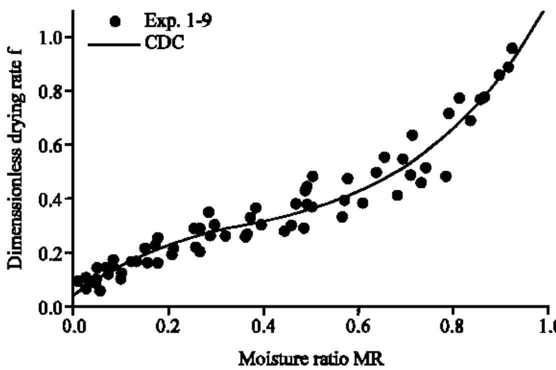

Fig. 9: Characteristic drying curve of *Ar. arborescens* leaves

$$f = 0.0491 + 1.3789\,MR - 2.49703\,MR^2 + 2.2753\,MR^3 \quad (15)$$

The criteria used to evaluate goodness of fit were the correlation coefficient (r = 0.9447) and the standard error (S_r = 0.0519).

Fitting of the drying curves: The drying data as moisture ratio MR versus drying time were fitted to ten thin layer drying models. The drying models coefficients were computed and presented in Table 7. The Logarithmic Eq. 16 was found to be the appropriate model describing the drying curves of *Ar. arborescens* leaves with an (r) of 0.9996 and χ^2 of 9.2073 10^{-5}. The coefficients of the accepted model for thin layer convective drying of the product were as below:

$$MR = a\exp(-kt) + c \quad (16)$$

Where:

$$a = 1.6702 - 0.0294\,\theta + 4.005\,10^{-4}\,\theta^2 \quad (17)$$

$$k = 0.1678 - 0.0073\,\theta + 8.350\,10^{-5}\,\theta^2 \quad (18)$$

$$c = 0.6483 - 0.0284\,\theta + 2.270\,10^{-4}\,\theta^2 \quad (19)$$

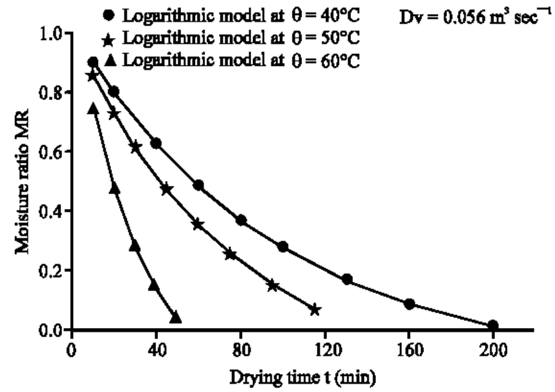

Fig. 10: Experimental and predicted moisture ratios obtained using the logarithmic model

The three expressions (Eq. 17-19) predicted well the Moisture Ratio (MR) at three drying temperatures 40, 50 and 60°C for *Ar. arborescens* leaves with an (r) of 1 and Sr of 0.

These results can be proved consequently from Fig. 10 which plotted Logarithmic predicted moisture ratios versus drying time at 40, 50 and 60°C. Also from this figure, it can be concluded that the predicted moisture ratio decreased with the increasing in the drying air temperature and consequently the drying time decreased.

Determination of effective diffusivity and activation energy: The slope of Eq. 10 is the measure of the diffusivity. Figure 11 gives the plot of ln (MR) versus drying time for the studied range of temperatures. The values of D_{eff} are shown in Table 8. It is apparent at constant drying air flow rate, that D_{eff} increases with the increase of drying air temperature. Similarly, at constant drying air temperature,D_{eff} increases with the increase of drying air flow rate. The effective diffusivities of *A. arborescens* varied in the range of 0.7125×10^{-11} to 6.2009×10^{-11} m^2 sec^{-1}. Similar results were obtained by Doymaz (2007) for pumpkin slices.

The activation energy (E_a) was calculated from the slope of the plot on ln(D_{eff}) versus reciprocal of the

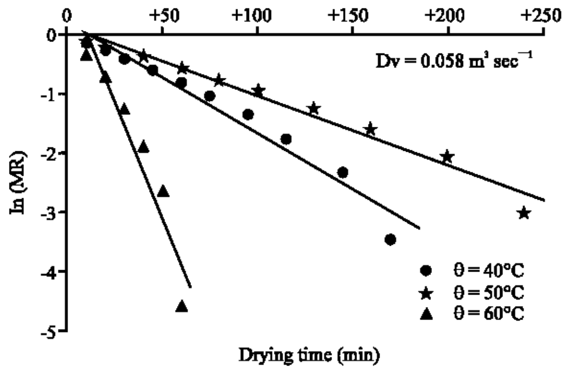

Fig. 11: Plot of ln(MR) vs drying time

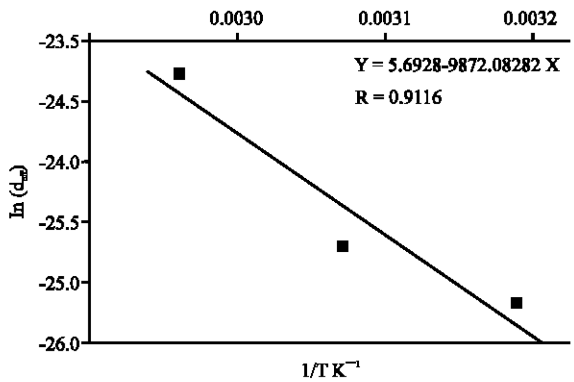

Fig. 12: Influence of drying air temperature on effective diffusivity

Table 8: Values of effective moisture diffusivity of *Ar. arborescens* leaves

Experiment no	Effective diffusivity (m^2 sec^{-1})
1	0.7125×10^{-11}
2	1.1405×10^{-11}
3	4.7783×10^{-11}
4	1.0770×10^{-11}
5	1.3645×10^{-11}
6	5.4713×10^{-11}
7	1.4439×10^{-11}
8	1.5707×10^{-11}
9	6.2009×10^{-11}

absolute temperature as shown in Fig. 12. The activation energy of *Ar. arborescens* leaves was found to be 82.0765 kJ mol^{-1}. This value is almost equal to activation energy of mint (82.93 kJ mol^{-1}) (Park *et al*., 2002).

CONCLUSION

The moisture sorption curves of *Ar. arborescens* leaves were experimentally investigated at three temperatures 30, 40 and 50°C. Among the sorption models chosen, the modified Oswin and the GAB models were the best models describing the sorption isotherms. The net isosteric heat of sorption of *Ar. arborescens* leaves decreases with the increase in moisture content and was found to be a polynomial function of moisture content for desorption and adsorption.

Thin-layer convective solar drying experiments were conducted for *Ar. arborescens* leaves in the temperature range of 40-60°C and three drying air flow rates (0.028, 0.056 and 0.084 m^3 sec^{-1}). Also, the drying air temperature was found to be the main factor influencing the drying kinetics.

From the results obtained, it was observed that only the falling drying rate period exists. The characteristic drying curve was obtained and the drying rate equation was calculated. This CDC can be used to generalize data for drying kinetics of *Ar. arborescens* leaves in a solar dryer with an auxiliary heating system. The goodness of fit of the observed values with ten thin-layer drying equations was evaluated. The Logarithmic equation was the best model to fit the experimental data and was recommended as the thin layer drying model for *Ar. arborescens* leaves.

The effective diffusivity values changed from 0.7125×10^{-11} to 6.2009×10^{-11} m^2 sec^{-1} within the given temperature range and increased as temperature increases. An Arrhenius relation with an activation energy value of 82.0765 kJ mol^{-1} expressed the effect of temperature on the effective diffusivity.

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NOMENCLATURE

a, b, c, n, k, k_0, k_1	:	Constants in drying models.
A, B and C	:	Coefficients in sorption models.
a_w	:	Water activity (-).
B_0, C_0, h_1, h_2	:	GAB coefficients.
CDC	:	Characteristic drying curve.
d.m.	:	Dry matter.
Dv	:	Drying air flow rate (m^3 sec^{-1}).
f	:	Dimensionless drying rate.
M	:	Moisture content at any time of drying (kg water kg^{-1} dry matter).
M_0	:	Initial moisture content(kg water kg^{-1} dm).
M_e	:	Equilibrium moisture content (kg water kg^{-1} dm)
M_f	:	Final moisture content (kg water kg^{-1} dm).
MBE	:	Mean bias error.
MR	:	Moisture ratio at any time of drying.
MRE	:	Mean relative error (%).
Q_{st}	:	Net isosteric heat of sorption (kJ mol^{-1}).

r : Correlation coefficient.
R : Universal gas constant (J/mol.K).
Rh : Ambient air relative humidity (%).
Sr : Standard error.
SEE : Standard error of estimate of moisture.
T : Absolute temperature (K).
t : Drying time (min).
θ : Temperature (°C).

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