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Experimental study of drying kinetics of *taraxacum officinale's* root dried in a forced convection solar dryer

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Abstract

Solar drying represents one of the friendliest environments and promising applications of solar energy. This is the reason why it is deemed as the oldest and most widely used applications. *Taraxacum officinale*'s roots are well known in traditional medicine and pharmacology. They are used around the world to treat different diseases. In order to prolonged the shelf life of this medicinal plant, reducing water activity and microbiological contamination process is needed; hence the solar dryer is used. This paper tackles the drying kinetics in different temperatures and airflows of this plant in a convection solar dryer. The results are represented in several mathematical models to determine the most suitable model that describes the best drying characteristic curve.

1. Introduction

The *Taraxacum Officinale* is a plant with incredible nutritional as well as therapeutic benefits. Thus, it is high time we rethought the way it is dried and conserved. Indeed, the *Taraxacum Officinale's* roots have been used as major therapeutic elements for years [1]. The Arabs and the Chinese are among the first to experience medical treatment with this plant. The Arab physicians used the *Taraxacum Officinale* to treat several illnesses such as the liver and the spleen in the X and XI centuries [2]. Additionally, research findings about this medicinal plant show that its roots prove to be an efficient diuretic and a powerful natural detoxing [3].

Once separated from the mother plant, medical herbs live on their own reserve and begin to dry gradually. According to the approximate conservation age, at this stage they are likely to be infected by microorganisms [4]. To overcome this matter, many new techniques for conservation have been developed. Among them, is the conservation of the product using physical methods like ionization and drying. Drying is the chemical engineering that seeks to eliminate the free water as well as the part of the bound water without changing the chemical composition of the product by either lightening the weight or diminishing the dangerous and undesirable chemical changes [5]. In this respect, several techniques and methods are elaborated in order to conserve the food in best optimal conditions at the lowest cost.

Solar drying field has witnessed a growing interest over recent years. Indeed, solar drying is considered to be the best alternative capable of surmounting the drawbacks of the other types of drying. As such, many have tackled the task of designing certain devices that are environment-friendly with a new ferocity. Therefore, forced convection appears as an innovative, time and energy-saving mode in solar crops drying [6]. Furthermore, forced convection is of high predominance in the fields of industry and agriculture.

In this paper, we seek to experimentally investigate the drying kinetics of the *Taraxacum Officinale*'s root behaviour during its drying in accordance with a controlled condition of temperature and airflow rate using an indirect forced convection solar dryer. This solar dryer is installed in the Teacher's Training College in Marrakesh. The experimental results were exploited in order to determine the drying Characteristic Curve, the rate of drying followed, and the mathematical model that is most suitable to the experimental curves.

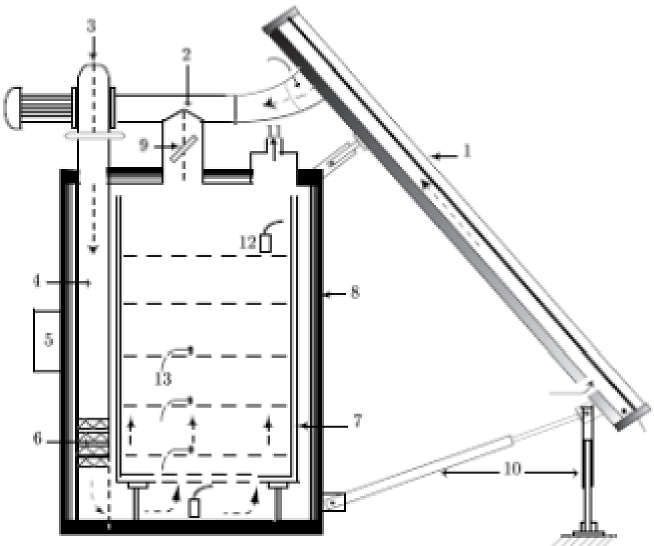
2. Material and Methods

2.1. Plant material

The *Taraxacum Officinale's* roots used in the study was collected in May 2019 in area "OULA SAID" (Settat, Morocco) at harvest stage maturity. This medicinal plant was obtained by the assistance of Mr. Mohammed Benouara, a phytotherapist in Settat,

2.2. Description of solar dryer

The system presenting in figure 1, starts working as soon as the degree of the temperature and the airflow are fixed on the box number (5). Then, the solar heated air is sucked by the fan (3) and drifts towards the samples. In other words, the heated air comes from the hole number (10). At this stage, the temperature of the air is increased in the solar captor (1). The measure of the degree of the temperature that exists in the drying room (8) is done by the thermocouple (12). Indeed, relying on an auxiliary heater is apparently unavoidable so as to maintain a constant air-drying temperature. If the temperature does not reach the targeted temperature, the auxiliary resistance (6) works and heats the air. This heated airflows towards the samples in drawer number (13) [6].



(1) Solar air collector,
(2) ventilation duct,
(3) fan,
(4) suction duct,
(5) control box,
(6) electric booster,
(7) stages,
(8) cabinet dryer,
(9) air shutter,
(10) air inlet,
(11) air outlet,
(12) thermocouple,
(13) sample holder.

Figure 1: The forced convective solar dryer implemented in ENS, Marrakech

2.3. Experimental protocol

The solar heated air flows upward the samples. It enters below the trays in the drying cabinet below. To keep a constant air-drying temperature, the use of an auxiliary heater is necessary. The calculation of the mass loss of the product on the tray during the experiment is done via a (±0.01 g). Then, the weight is measured by removing the product from the drying cabinet each 10 min until the weight became stable [7].

The drying curves are the ones that represent the variations of the moisture content MC in function of time t. The drying curves are also helpful in defining the drying rate in function of time or of the moisture content. Throughout the experiments, it is important to follow the evolution of the wet mass of the product Mh while being dried. The final moisture content can only be attained through successive weighing of the wet mass of the product Mh [8].
In order to get the dry mass Ms of the product, this later must be put at the end of a test in an oven heated to a temperature that equals 105 ° C. All the experimental information [9, 10] is included in this curve. It is of paramount importance to determine an optimal value of the moisture content for each sample to ensure the safety and the stability of the product so that it can keep its full nutritional and organoleptic qualities [11].Moreover, the conditions of installing the system as well that of drying the product must unmistakably reach this optimum humidity value.

2.4. Determination of drying curves

During this experiment, it is necessary to determine the *Taraxacum Officinale* root drying curves. They are considered as powerful tools to analyze the changes in masses, the mass transfers with the environment under different conditions [10] as well as the influence of the temperature and humidity on the drying behavior of the *Taraxacum Officinale* root. The drying curves can be represented by several curves. In this study, the most important curves must be carefully represented.
First, it is necessary to represent the variations of the moisture content MC as a function of the drying time t while the moisture content can be illustrated by the equation below:

$$MC(t) = \frac{Mh - Ms}{Ms} \tag{1}$$

Second, the curves should represent the variation of the drying rate in function of the moisture ratio as well as the moisture content. The equations (2) and (3) show the relation between them and the moisture content respectively:

$$DR(t) = \frac{dMC}{dt} \tag{2}$$

$$MR = \frac{MC - MC_e}{MC_0 - MC_e} \tag{3}$$

Finally, the characteristic drying curve is given by a single normalized drying rate (f) curve under different drying conditions. This later can be plotted by $f = \mathrm{f}(MR)$ where [12]:

$$f = \frac{\left(-\frac{dMC}{dt}\right)_t}{\left(-\frac{dMC}{dt}\right)_0} \tag{4}$$

Where:
M_h: The mass of the sample after a specified drying time
M_s: The dry mass after 24h in over at 105°C
MC_e: The moisture content at the equilibrium
MC_0: The initial moisture content
MR: The moisture ratio
DR: The drying rate

2.5. Mathematical modelling of solar drying curves

Analysing the drying process can be done through a large number of empirical or semi-empirical models. The drying time factor plays a significant role in describing both the kinetics of drying and the prediction of moisture ratio. In this regard, using the thin layer drying for medicinal plants is of extreme significance in portraying the shape as well as the scope of the drying curves; hence, establishing a suitable empirical equation. Additionally, the following parameters most particularly the highest correlation coefficient (r) and the standard error of estimate (SEE) are helpful in choosing the sustainable model that would better describe the drying process. These equations are displayed on the flowing expressions [12, 10].

Table1: Mathematical models for drying curves

Model	Equation	Number	Reference
Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	5	[12]
Henderson and Pabis	$MR = a\exp(-kt)$	6	[12]
Logarithmic	$MR = a\exp(-kt) + c$	7	[11]
Midilli–Kucuk	$MR = a\exp(-kt^{n}) + bt$	8	[11]
Newton	$MR = \exp(-kt)$	9	[12]
Page	$MR = \exp(-kt^{n})$	10	[10]
Two-term	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	11	[10]
Wang and Singh	$MR = a + at + bt^{2}$	12	[11]

$$r = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{i,pre} - \overline{MR}_{i,exp}\right)^2}{\sum_{i=1}^{N}\left(MR_{i,exp} - \overline{MR}_{i,exp}\right)^2}} \quad (13)$$

$$\overline{MR}_{i,\exp} = \frac{1}{N}\sum_{i=1}^{N} MR_{i,\exp} \quad (14)$$

$$\overline{MR}_{i,pre} = \frac{1}{N}\sum_{i=1}^{N} MR_{i,pre} \quad (15)$$

$$SEE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{i,exp} - MR_{i,pre}\right)^2}{d_f}} \quad (16)$$

Where:

$MR_{i;exp}$ is the experimental moisture ratio.

$MR_{i;pre}$ is the predicted moisture ratio.

N is the number of data points.

df is the number of degrees of freedom of the regression model.

3. Results and discussion

3.1 The drying curves

The figure that appears above represents the variation of the moisture content in function of the drying time. We can see from this figure that the moisture content decreases with the increase of the temperature. It also decreases with the increases of the airflow. In this respect, these two-drying parameters affect the moisture content of the *Taraxacum Officinale* root. Additionally, when analysing the figure, it is easy to assume that the airflow has a low impact on the *Taraxacum Officinale* root drying at low temperature; while it has an important impact at high temperature. These finding has been mentioned by many scientific searchers [9, 10, 12].

The figure 3 shows the relation between the variation of drying rate and the moisture content at different temperatures (60, 70 and 80 °C) and airflows (150 and 300 m^3h^{-1}). The outcome of this curve is that the drying rate of *Taraxacum Officinale* root increases when the drying temperature and the airflow increase. As a result, the drying kinetics of *Taraxacum Officinale* root is influenced by the drying airflow and the temperature. Several studies have already mentioned the same results [9, 11 and 13].

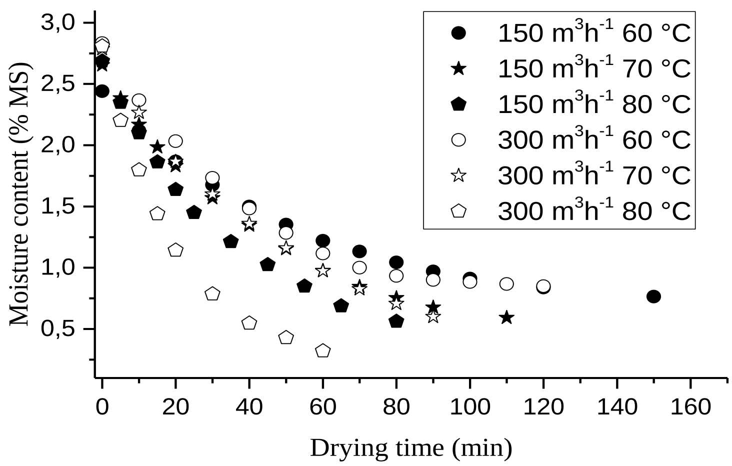


Figure 2: The moisture content variation in relation to drying time

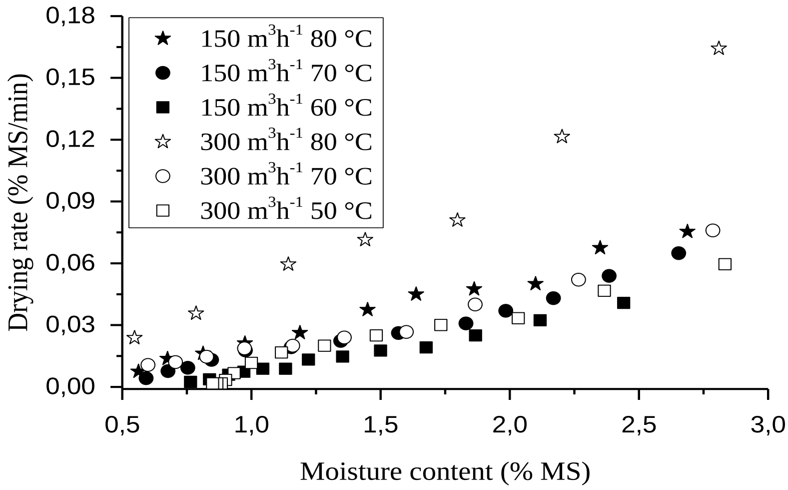


Figure 3: The variation of the drying rate in function of the moisture content

3.2. Determination of the characteristic drying curve

The characteristic drying curve aims at determining a law of drying based on several experiments by different drying conditions. The method involves normalizing the kinetics drying of drying *Taraxacum Officinale* root by an empirical model, a polynomial of order 3and regression from experimental data. In the study, we counted on using the Origin 6.1 software and the non-linear optimization method of Levenberg-Marquard to obtain the characteristic drying curve as it is plotted in figure 4. Figure 4 shows all experimental data of solar drying curves of the *Taraxacum Officinale* root. It obtained through the representation of the moisture ratio and the dimensionless drying rate. For the different drying conditions, falling into a tight band indicates that the effect of variation in different conditions is small over the range tested.

The following equation presents the coefficient values of the empirical model:

$$f = 0.05908 + 1.21447MR - 1.2563MR^2 + 0.99106MR^3 \tag{17}$$

This model proves to be suitable to the solar drying data through several powerful statistical parameters (Residual Sum of Squares (RSS), R-Square (r) and Adj. R-Square (radj)) as it is displayed in the equations below:

$$RSS = 0.1008 \tag{18}$$

$$r = 0.98048 \tag{19}$$

$$r_{adj} = 0.97952 \tag{20}$$

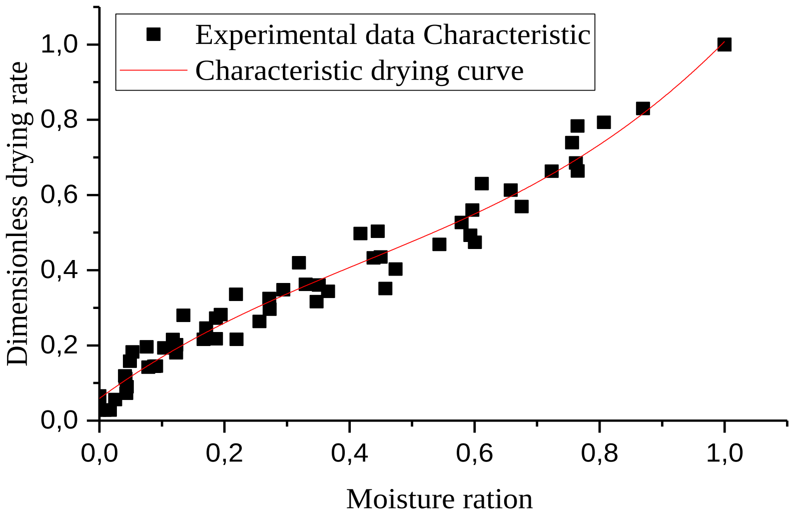


Figure 4: Characteristic drying curve of the *Taraxacum Officinale* root

3.3. Fitting of the drying curves

It is undeniable that modelling an experimental data is the best way to overcome the phenomena and predict all possible outcomes. In this respect, eight empirical and semi-empirical models have been selected from the literature in order to obtain the most suitable model that can represent the *Taraxacum Officinale* root drying curves. The selection was based on two statistical parameters: SEE and r as selection criteria. The drying constants and the values of r and SEE of the eight models are determined using the non-linear optimization method Marquard-Levenberg using appropriate software for all the experimental points [7, 8]. All the parameters mentioned before are summarized in table 3.

Table1: Mathematical models for drying curves

Models	Parameters	80°C 150 $m^3.h^{-1}$	80°C 300 $m^3.h^{-1}$	70°C 150 $m^3.h^{-1}$	70°C 300 $m^3.h^{-1}$	60°C 150 $m^3.h^{-1}$	60°C 300 $m^3.h^{-1}$
Newton	k	0.0350	0.0556	0.0272	0.0287	0.0218	0.0303
	r	0.9968	0.9987	0.9966	0.9937	0.998	0.9944
	ESM	0.0262	0.0179	0.0277	0.0368	0.0197	0.0348
Page	k	0.0258	0.0450	0.0193	0.0165	0.0153	0.0134
	n	1.0918	1.0724	1.0928	1.1479	1.0884	1.2191
	r	0.9980	0.9993	0.9978	0.9962	0.9990	0.9988
	ESM	0.0218	0.0142	0.0233	0.0301	0.0144	0.0171
Henderson and Pabis	a	1.0157	1.0091	1.0130	1.0203	1.0142	1.0354
	k	0.0357	0.0562	0.0276	0.0293	0.0221	0.0313
	r	0.9970	0.9987	0.9968	0.9940	0.9981	0.9951
	ESM	0.0267	0.0187	0.0283	0.0381	0.0198	0.034
Logarithmic	a	1.0960	1.0499	1.0997	1.1665	1.0648	1.0847
	k	0.0286	0.0499	0.0215	0.0203	0.0188	0.0261
	c	-0.1030	-0.0488	-0.1122	-0.1790	-0.0682	-0.0706
	r	0.9995	0.9999	0.9996	0.9995	0.9999	0.9985
	ESM	0.0115	0.0067	0.0097	0.0118	0.0052	0.0199
Two-term	a	0.5726	0.5542	0.5565	0.5485	0.5576	0.5672
	k_0	0.0357	0.0562	0.0276	0.0393	0.0221	0.0314
	b	0.4431	0.4548	0.4564	0.4718	0.4567	0.4681
	k_1	0.0357	0.0561	0.0276	0.0293	0.0221	0.0312
	r	0.9970	0.9987	0.9968	0.9940	0.9981	0.9951
	ESM	0.0302	0.0221	0.0313	0.0440	0.0219	0.0376
Wang and Singh	a	-0.0264	-0.0402	-0.012	-0.021	-0.0157	-0.0209
	b	$1.8002\ 10^{-4}$	0.0004	$1.0178\ 10^{-4}$	$1.1287\ 10^{-4}$	$6.2209\ 10^{-5}$	$1.0886\ 10^{-5}$
	r	0.9949	0.9925	0.9961	0.9968	0.994	0.9970
	ESM	0.0351	0.0451	0.0310	0.0275	0.0356	0.0264
Diffusion Approximation	a	-3.6702	-4.4270	-5.0902	-6.3105	-10.8119	-7.4397
	k	0.0546	0.0817	0.0418	0.0464	0.0321	0.0526
	b	0.9037	0.9271	0.9259	0.9276	0.9644	0.9243
	r	0.9982	0.9994	0.9981	0.9965	0.9992	0.9988
	ESM	0.0218	0.0136	0.0222	0.0309	0.0133	0.0173
Midilli-Kucuk	a	1.0014	0.9982	0.9940	1.0003	0.9961	0.9899
	k	0.0355	0.0524	0.0254	0.0324	0.0189	0.0147
	n	0.9557	0.9994	0.9790	0.8917	1.0168	1.1812
	d	-0.0012	$-7.0375\ 10^{-4}$	$-8.4993\ 10^{-4}$	-0.0019	-0.0003	$-2.0215\ 10^{-4}$
	r	0.9997	0.9999	0.9996	0.9999	0.9998	0.9992
	ESM	0.0101	0.0073	0.0105	0.0053	0.0663	0.0148

According to table 3, it is obvious that the Midilli-Kucuk is the best model to fit the experimental data obtained from the experiments using the convective solar dryer to dry the *Taraxacum Officinale* root. This outcome can be demonstrated by the highest r and a low value of SEE of Midilli-Kucuk model.
The coefficients of Midilli-Kucuk model at airflow 150 $m^3.h^{-1}$:

$$a = 5\times10^{-5}T^2 - 0.0064T + 1.2082$$

$$k = 2\times10^{-5}T^2 - 0.0017T - 0.0555$$

$$d = -7\times10^{-6}T^2 + 0.001T - 0.0336$$

$$n = 7\times10^{-5}T^2 - 0.0132T - 1.5481$$

The coefficients of Midilli-Kucuk model at airflow 300 $m^3.h^{-1}$:

$$d = 2\times10^{-5}T^2 - 0.0027T + 0.0912$$

$$n = 0.002T^2 - 0.2871T + 11.259$$

$$k = 1\times10^{-5}T^2 + 0.0003T - 0.0432$$

$$a = -6\times10^{-5}T^2 + 0.0092T + 0.665$$

These models have been established by Midilli-Kucuk it was found to be the most suitable one for this experiment. It will allow the prediction of moisture content for different drying times this could only be possible for those temperatures (60, 70, 80); whereas, the equation above will allow the prediction of the Midilli-Kucuk model coefficient value for different temperatures at two airflows 150 and 300 m^3h^{-1}. Those results were also found in other studies [8, 12, 13].

Conclusion

In conclusion, it is crystal clear that solar drying is an efficient solution to the conservation of plants. Accordingly, the study of the *Taraxacum Officinale* root kinetic drying by a forced convection solar dryer is indispensable to analyse the drying behaviour of the *Taraxacum Officinale* root and modelling of its drying kinetics.

The characteristic drying curve gives valuable information for the prediction of the drying rate for other experimental conditions other than those in which our experiments were carried out. Furthermore, the statistical parameters demonstrate that the polynomial model with degree 3 is suitable to the experimental data.

In the same token, eight empirical and semi-empirical models were tested. In this regard, The Midilli-Kucuk model showed a good correlation with the experimental curves with the highest r and the lowest SEE.

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