An Experimental and Numerical Study on the Drying of Celery (*Apium Graveolens L.*) Growing in Southern Tunisia

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ABSTRACT

The present work experimentally investigates the curves of the drying kinetics of celery leaves (*Apium Graveolens L.*) in a drying convective oven. These curves were determined at 50°C, 60°C, and 70°C. For the fitting of the experimental results, the Lewis, Handerson, and Pabis, Page, Midilli &Kucuk, Logarithmic, Modified Page, Wang, and Singh and Two Terms models were used. The Midilli & Kucuk model provided the best fit for the experimental results. The effective water diffusion coefficient (D_{eff}) varied from 3.65×10^{-10} m^2/s to 7.29×10^{-10} m^2/s in the considered temperature range. The higher temperature gave a higher effective water diffusion coefficient and Drying Rate (DR). The activation energy calculated using an exponential expression based on the Arrhenius equation was 31.72 kJ/mol. The Characteristic Drying Curve (CDC) was also determined as a three-degree polynomial.

Keywords-Apium graveolens L.; drying curves; water diffusion coefficient; activation energy; Midilli &Kucuk

I. INTRODUCTION

Celery is a plant of the Apiaceae family [1]. It is native to the Mediterranean and Middle Eastern regions but is now cultivated worldwide [2]. The presence of compounds, such as limonene, selinene, frocoumarin glycosides, flavonoids, and vitamins A and C are the reason that celery is the most widely used plant in traditional medicine [3]. The production of celery has gradually increased due to the rapid development of industrial planting [4]. One of the most critical stages, where crop management can be improved, is that of drying [5]. Drying reduces the amount of food moisture to prevent the growth of microorganisms, while enzymatic activity and chemical reaction rates are also significantly reduced [6]. The most accurate way to characterize a product's drying behavior is through the experimental measurement of its drying kinetics. In this study, experiments were carried out on drying celery leaves at three different temperatures in a convective drying oven. The objectives of the present work are: firstly, to experimentally and numerically study the drying kinetics to determine the most appropriate kinetics model. Secondly, to investigate the calculated effective water diffusion coefficient and activation energy, and finally, to identify the CDC of celery leaves.

II. MATERIALS AND METHODS

A. *Plant Matter*

The fresh celery used in this work was collected from a local farmer in the region of Gabes, southern Tunisia (33°49'60" N and 9°45'0" E), in February. The leaves were separated from the rest of the plant to be utilized in the experimental study.

B. *Experimental Determination of Drying Kinetics*

The celery leaves were previously cleaned and cut into small pieces. The plant material was oven-dried at temperatures of 50°C, 60°C, and 70°C. The drying kinetics were determined according to the mass variation measurements of the samples over time using a balance with a precision of 0.001 g. The curves of the drying kinetics are graphically plotted. The dry base moisture content, noted as X_{db}, was calculated by [7]:

$$X_{db} = \frac{(M_i - M_d)}{M_i} \quad (1)$$

where M_i is the initial wet weight of the product (g), and M_d is the final dry weight (g). M_d is determined with a precision balance after drying the plant material in an oven at 105°C for 24 hours. The DR reflects the evolution of the moisture content as a function of time and is calculated by:

$$DR = \frac{\Delta(X_{db})}{\Delta t} \quad (2)$$

C. Determination of the Effective Water Diffusion Coefficient and Activation Energy

The effective water diffusion coefficient indicates a material's ability to dehydrate under specific drying conditions and is a key parameter in designing an optimal drying process [8]. To determine the effective water diffusion coefficients, the Moisture Ratio (MR) was calculated at each time point by [7]:

$$MR = \frac{(X - X_e)}{(X_0 - X_e)} \quad (3)$$

where X is the moisture content at time t, X_0 is the initial moisture content, and X_e is the moisture content at equilibrium. According to (4), the effective water diffusion coefficient (D_{eff}) is calculated from the slope of the straight line showing ln (MR) as a function of the drying time (s) [9]:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 \times D_{eff}}{4 \times L^2}\right) \times t \quad (4)$$

where D_{eff} denotes the effective water diffusion coefficient (m^2/s), L is half of the thickness of the plant material layer (m), and t is the time (s). According to Arrhenius' Law (5), the activation energy can be calculated from the slope of the straight line obtained when plotting ln (D_{eff}) as a function of (1/T) [9].

$$D_{eff} = D_0 \, e^{\left(-\frac{Ea}{R.T}\right)} \quad (5)$$

where D_0 is the Arrhenius equation pre-exponential factor (m^2/s), Ea is the activation energy (kJ mol^{-1}), T is the temperature (K), and R is the universal gas constant (8.314×10^{-3} kJ mol^{-1} K^{-1}).

D. Characteristic Dring Curve

Based on the tests conducted and the results obtained, a CDC was developed to describe the drying behavior of celery leaves through steaming. This method normalizes the DR as a function of the MR, aligning with the various measured values around an average trend line, known as the CDC. This approach allows for a more consistent and accurate representation of the drying process [10].

E. Modeling of Drying Kinetics

The modeling of drying kinetics enables predicting the drying kinetics of many agricultural products and food materials as well as evaluating the endpoint of the process [11]. To perform the fitting of the experimental points, the software "Curve Expert 1.4" was used, and the thin-layer drying models given in Table I were applied [12, 13].

TABLE I. DRYING KINETICS MODELS [12, 13]

Name of the model	Expression
Lewis	MR = exp (-kt)
Henderson and Pabis	MR = a exp (-kt)
Page	MR = exp (-kt^n)
Midilli &Kucuk	MR = a exp (-kt^n) + bt
Logarithmic	MR = a exp (-kt) + c
Modified Page	MR = exp (-kt)
Wang and Singh	MR = 1 + at + bt^2
Two Terms	MR = a exp (-k_0t) + b exp (-k_1t)

The model that best represents the drying behavior of celery leaves was selected by comparing the correlation coefficients (r) and the standard error (S) for each model.

III. RESULTS AND DISCUSSION

A. Variation of Moisture Content

Figure 1 shows the variation of the dry base moisture content of celery leaves over time at each drying temperature. Three repetitions were performed and the data provided were an average of the obtained results for each temperature. It is demonstrated that the water content of the product decreases rapidly during the first drying times and then this reduction is performed at a slower pace. It is also noted that increasing the drying temperature allows celery leaves to reach the phase of constant water content more quickly. Similar results have been reported in several studies, such as those for celery slices and the drying of purslane [14, 15].

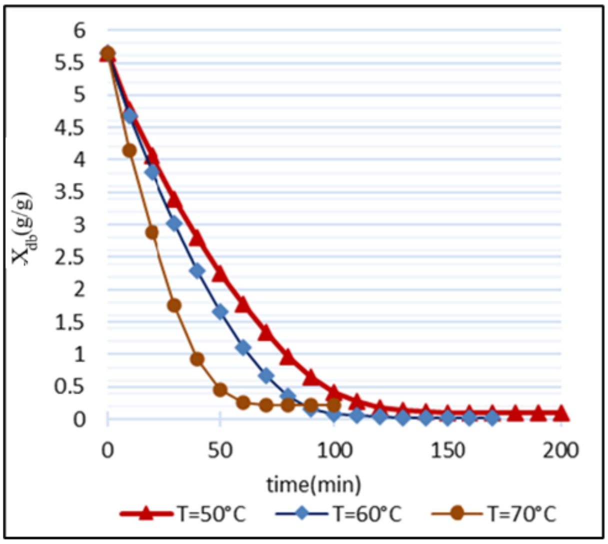

Fig. 1. Variation of water content with time.

Figure 2 depicts the DR at different dry base moisture content for various temperatures. It seems that the DR is higher at the beginning of the drying process for all temperatures provided. Similar results were documented in [11], where it was explained that with the progress in drying time, the product becomes dry, hindering heat penetration into the matrix. This leads to a decrease in the DR. It is observed that the DR increases when the temperature increases and that there is no constant rate period in the drying of celery leaves in a convective oven. This agrees with the results reported in [14]. According to [16], the absence of a constant rate period shows that the internal moisture diffusion phenomenon is dominant and controls the drying process.

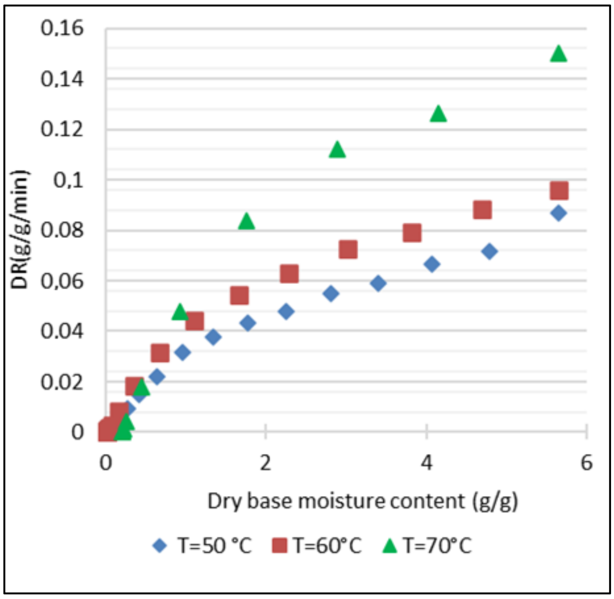

Fig. 2. Variation of DR with water content.

B. *Effective Water Diffusion Coefficient and Activation Energy*

Figure 3 portrays the variation of ln (MR) over time for the three drying temperatures studied. By determining the slopes of the regression lines for ln (MR) versus time at each temperature, the corresponding diffusion coefficients were calculated. The effective water diffusion coefficients obtained are listed in Table II.

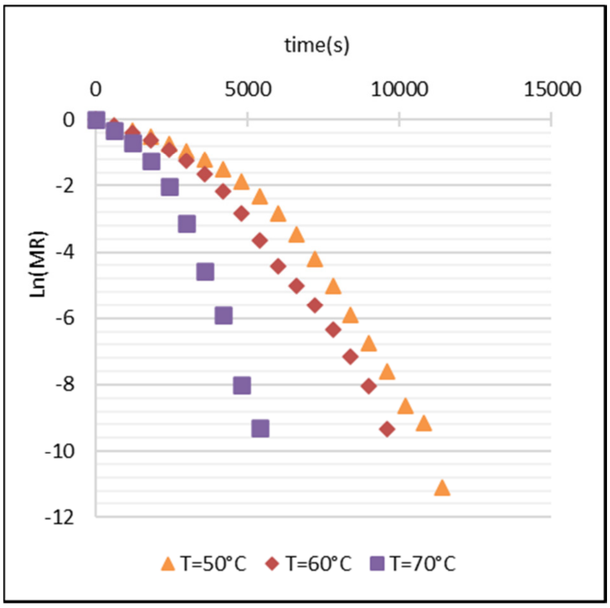

Fig. 3. Variation of ln (MR) with time at different temperatures.

It is evidenced that the diffusion coefficient increases with temperature. The diffusivity or the ability of water to leave the wet body to the outside environment, under the effect of heat, becomes higher. The values obtained for the effective diffusion coefficients are comparable with those recorded in [17]. Effective diffusion coefficients of water ranging from 9×10^{-10} m^2/s to 2.337×10^{-9} m^2/s were noted in the case of drying parsley leaves at 50°C-70°C temperatures. Authors in [18] documented effective diffusion coefficients of water of 3.098×10^{-10} m^2/s and 7.744×10^{-10} m^2/s in the range of 40°C – 60°C for muña leaves. The activation energy was found to be 31.72 kJ/mol, which is comparable with the 36.09 kJ/mol found in [11] for celery leaves, and 33.7 kJ/mol in [19] for blood orange slices.

TABLE II. EFFECTIVE WATER DIFFUSION COEFFICIENTS

T (°C)	D_{eff} (m^2/s)
50	3.65×10^{-10}
60	4.05×10^{-10}
70	7.29×10^{-10}

C. *Characteristic Drying Curve (CDC)*

Figure 4 exhibits that the CDC of celery leaves in a convection drying oven at 50°C-70°C temperatures was obtained from drying experimental data according to [20].

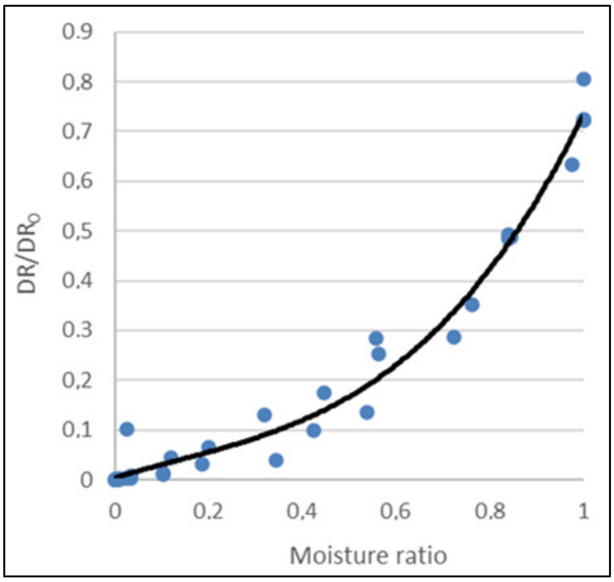

Fig. 4. CDC of celery leaves.

The smoothing of the CDC enables determining the equation of the latter, which is a three-degree polynomial:

$$\frac{DR}{DR_0} = 0.7254 \times MR^3 - 0.282 \times MR^2 + 0.2824 \times MR + 0.0037 \quad (6)$$

D. *Fitting of the Drying Kinetic Curves*

To choose the model that is the best fit for the experimental data on drying of celery leaves, eight models given in the literature were tested. Table III summarizes the results of smoothing the experimental points of the drying kinetics of celery leaves. These results include the drying model coefficients, correlation coefficient, and standard error. Table III shows that all the models demonstrate a good correlation with the experimental results. Indeed, all the correlation coefficients are close to uniting. The model that presents the highest correlation coefficient and the lowest standard error constitutes the best fit for experimental data. A comparison of the (r) and (S) values of the different models presented in Table III reveals that the Midilli & Kucuk model is a better fit for the experimental results at temperatures of 50°C, 60°C, and 70°C, which agrees with other studies, such as those carried out in [21] for celery leaves and in [22] for dried banana.

TABLE III. PARAMETERS OF THE MODELS AND STATISTICAL RESULTS

Model	T °C	r	S	Constants
Page's	50	0.9981	0.0201	$k=5.743\times10^{-3}$; $n=1.3219$
	60	0.998	0.018	$k=5.9783\times10^{-3}$; $n=1.3788$
	70	0,9990	0.0167	$k=1.1766\times10^{-3}$; $n=1.3931$
Henderson and Pabis	50	0.9914	0.0428	$k=2.2595\times10^{-2}$; $a=1.0623$
	60	0.9905	0.0465	$k=2.7476\times10^{-2}$; $a=1.0674$
	70	0.9908	0.0509	$k=4.5661\times10^{-2}$; $a=1.0471$
Lewis	50	0.9890	0.0459	$k=2.1369\times10^{-2}$
	60	0.9883	0.0499	$k=2.5978\times10^{-2}$
	70	0.9896	0.0511	$k=4.3956\times10^{-2}$
Two terms	50	0.9967	0.0273	$a=1.8573$; $k_0=-9.9707.10^{-03}$ $k_1=1.2950.10^{-2}$
	60	0.9954	0.0335	$a=-1.3111$; $k_0=-1.1569\times10^{-2}$ $k_1=1.6317\times10^{-2}$
	70	0.9961	0.0354	$a=-1.2947$; $k_0=-1.9075\times10^{-2}$ $k1=-2.7291\times10^{-2}$
Midilli & Kucuk	50	0.9987	0.0174	$a=9.7475\times10^{-1}$; $b=-9.5618\times10^{-5}$ $n=1.3344$; $k=5.1715\times10^{-3}$
	60	0.9989	0.0168	$a=9.8003.10^{-1}$; $b=-7.8409$ $n=1.3948$; $k=5.4026.10^{-3}$
	70	0.9992	0.0169	$a=9.9327\times10^{-1}$; $b=-1.5659\times10^{-4}$ $n=1.2193\times10^{-2}$; $k=1.374$
Wang and Singh	50	0.9967	0.0264	$a=-1.4272\times10^{-2}$; $b=4.9092\times10^{-5}$
	60	0.9959	0.0305	$a=-1.7231\times10^{-2}$; $b=7.1143\times10^{-5}$
	70	0.9975	0.0268	$a=-2.9488\times10^{-2}$; $b=2.0938\times10^{-4}$
Logarithmic	50	0.9961	0.0297	$a=1.1065$; $c=-7.0154\times10^{-2}$ $k=1.8726\times10^{-2}$
	60	0.9949	0.0351	$a=1.1115$; $c=-6.6448\times10^{-2}$ $k=2.3116\times10^{-2}$
	70	0.9955	0.0382	$a=1.1062$; $c=-7.6029\times10^{-2}$ $k=3.7802\times10^{-2}$
Modified Page	50	0.9896	0.047	$k=3.5817\times10^{-2}$; $n=5.9655\times10^{-2}$
	60	0.9883	0.0515	$k=3.9491\times10^{-2}$; $n=6.5779\times10^{-1}$
	70	0.9896	0.054	$k=5.3153$; $n=8.2692\times10^{-1}$

k, k_0, k_1, a, n, b, and c are constants of the models.

IV. CONCLUSIONS

The characteristics of thin-layer drying kinetics of celery leaves from southern Tunisia were studied using a drying convective oven. The effect of drying temperatures ranging between 50°C and 70°C was investigated. Eight models were used to correlate the experimental data of the drying kinetics. The fitting of these curves led to the conclusion that the model of Midilli & Kucuk acts as the best fit for the experimental results, with the highest correlation coefficient and the lowest standard error. The results revealed that the Drying Rate (DR) is higher at the beginning of the drying process for all temperatures and that it increases when the temperature increases, which agrees with other results reported in the literature. The effective water diffusion coefficient calculated using the second Fick's Law varies from 3.65×10^{-10} m^2/s to 7.29×10^{-10} m^2/s for temperatures ranging from 50°C to 70°C. The experimental drying curves were normalized to obtain the Characteristic Drying Curve (CDC). Exploring the energy and exergy performance of drying celery leaves growing in southern Tunisia will be the subject of our future work.

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