

## EFFECT OF MEDIUM-RANGE TEMPERATURES ON THE CONVECTIVE DRYING KINETICS OF CELERY LEAVES AND STEMS

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**ABSTRACT.** This work focuses on the comparative description of convective thin-layer drying of celery leaves and stalks at 40, 50 and 60°C, respectively. Close to 100% moisture loss was recorded, yet total process time shortens at elevated temperatures. The adjusted determination coefficient, the root mean square error and the hybrid fractional error deviation, respectively, were simultaneously employed as selection criteria for the most suitable kinetic model. The empirical parabolic model was chosen to describe drying kinetics of both plant parts. Its parameters and their temperature dependence were quantified. Calculated drying parameters reflect the results of ANOVA testing. Effective water diffusivity coefficients are 3 orders of magnitude higher for stem and its drying activation energy is 34% lower. Specific energy consumption values prove that drying of stems is more energy efficient than that of leaves.

**Keywords:** *Apium graveolens*, Convective drying, Kinetic modeling, Leaf and stem

### INTRODUCTION

*Apium graveolens*, commonly known as celery, is a widely grown and consumed biennial plant of the *Apiaceae* family [1-4]. Because of its unique flavor, well-documented biologic proprieties, and low caloric content [2,5-7],

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all parts of it (leaf, stem, root, seeds) are of economic importance. Thus, market demand and supply are high, either in its fresh, dried, or other commercial form.

Besides the fresh plant, the Romanian celery market is characterized by two major product groups. The first targets its direct use as a spice and consists of 0.1, 1 Kg packages of dehydrated celery leaves, roots and/or seeds, either as such or as a powder, sometimes also in salty mixtures. The second refers to phytopharmaceutical products, for example hydroalcoholic extracts. In either case, appropriately dried celery parts serve as raw material. Hence, there is a clear industrial need for rapid, cost-effective, and highly efficient drying methods, capable of reducing the plant's moisture content below 10%, yet also ensuring the retention of its phytochemical characteristics.

The most common procedures are: the conventional hot-air (forced convective) drying, open-air drying at room temperature, freeze-drying (lyophilization), vacuum drying, sublimation drying, and microwave drying [3,5,7], respectively.

Research in the field focuses on two directions. One targets the retention of phytochemical composition, by investigating antioxidant activity, total phenolic and/or flavonoid content, as well as antibacterial activity of various dried celery parts [7,8]. Some studies also evaluate organoleptic properties and mechanical changes, such as grindability [7]. Ultimately, the retention of these attributes depends on the drying procedure and its specific operational parameters (e.g., drying time, temperature, microwave power, etc.) [9]. Another research direction targets the understanding of the moisture removal process itself, by explaining experimental data with various theoretical, semi-theoretical and/or empirical drying kinetic models [1,10,11]. It describes drying rates and mechanisms as a function of the specific procedure and its parameters [1,6,11,12].

Despite the multitude of investigated techniques, convective drying remains the most commonly used [13]. Its wide industrial practicality relies on commercially available and affordable equipment, designed for high quantity throughput. The overall temperature range reported in the literature spans from 25 °C to 120 °C, yet existing studies focus either on its lower or higher values end [8,13]. Low temperature convective drying is less energy consuming, but more time demanding. On the other hand, the use of elevated temperature might save time, but compromises phytochemical characteristics, such as antioxidant activity or chlorophyll content [3,7]. Therefore, operation at medium-range temperature might offer a solution to affordable energy / time costs, while retaining the plant's desired bioactive proprieties. However, no thorough and systematic such study has been reported yet.

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Furthermore, while drying various celery parts (leaf, stem, root, or seeds) is well described, research typically focuses strictly on either of these. No comparative data can be found in the literature, detailing the distinct drying behaviours of various morphological celery components under identical experimental conditions. This is a significant gap since simultaneous drying of various plant parts, such as leaves and stalks for instance, makes sense from an economic point of view. On the Romanian market for example, both the commercially available dehydrated spices and hydro-alcoholic extracts are based on mixtures of all parts [14,15,16,17].

The present study aims a comparative kinetic study between *Apium graveolens* leaves and stalks, under the same mid-range temperature, forced convective drying conditions. As such, it tries to bridge both data gaps described above.

## RESULTS AND DISCUSSION

### General characteristics of the drying process

Samples of 10 g celery leaf and stem were subjected to forced convective drying, under identical experimental conditions, at 40, 50 and 60°C, respectively. Each sample's residual mass was recorded against the total drying time, leading to the kinetic curves presented in Figure 1 and Figure 2 for leaves and stalks, respectively.

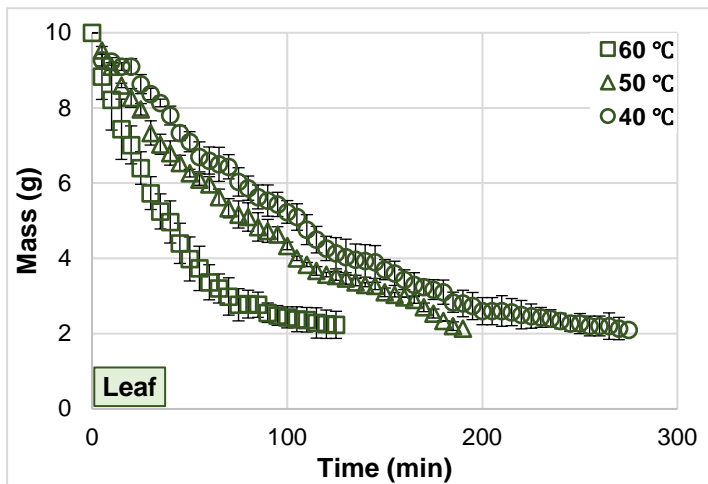
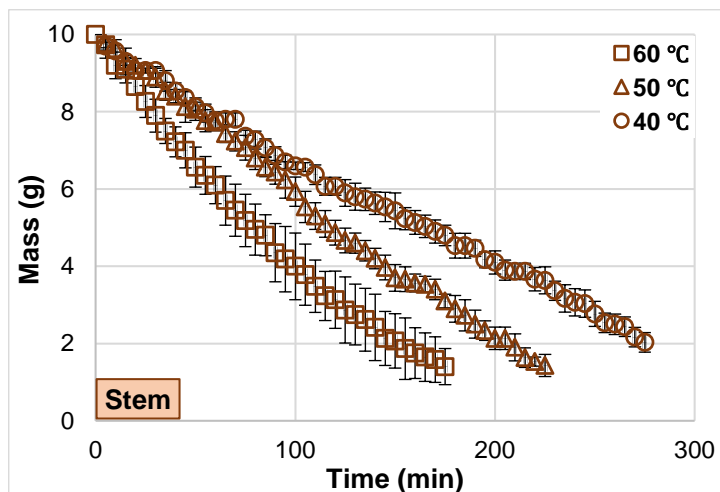


Figure 1. Leaf sample retained mass versus total drying time.



**Figure 2.** Stem sample retained mass versus total drying time.

These present mean values and their respective error bars for 3 distinct measurements at 40 and 50°C, whereas the 60°C data correspond to sets of 6 repetitions. The error bar values prove that data variability decreases with temperature.

Data in Figures 1 and 2 were subjected to mono- and bi-factorial statistical ANOVA testing, to determine whether the two independent variables (temperature and type of plant material) affect the drying kinetic behavior in a statistically significant manner, or whether they interact in determining its shape. The results, translated into probability p-values, are presented in Table 1. Lower than 0.05 values mean statistically significant effect and are correlated with the  $H_1$  hypothesis, whereas the opposite is true for higher than 0.05 values, for which hypothesis  $H_0$  is accepted [18].

All mono-factorial tests prove that both parameters affect significantly drying kinetics, but more so the temperature. The bi-factorial test proves the same yet demonstrates that there is no interaction (or at least at the threshold of statistical significance) between the 2 independent variables in shaping the kinetics of this particular drying process (p of 0.083 very close to the threshold of 0.05).

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**Table 1.** Results of ANOVA testing for data given in Figures 1 and 2; probability p-values and their corresponding accepted hypotheses.

Type of ANOVA test	p-value *	Accepted hypothesis
<i>Mono-factorial testing of either the effect of temperature or of plant material type</i>		
Effect of temperature – Leaf	$3.69 \times 10^{-5}$	H <sub>1</sub>
Effect of temperature – Stem	$9.59 \times 10^{-4}$	H <sub>1</sub>
Effect of plant material type – 40°C	$1.77 \times 10^{-2}$	H <sub>1</sub>
Effect of plant material type – 50°C	$6.32 \times 10^{-4}$	H <sub>1</sub>
Effect of plant material type – 60°C	$2.87 \times 10^{-4}$	H <sub>1</sub>
<i>Bi-factorial testing of combined effects of temperature and plant material type</i>		
Effect of temperature	$2.98 \times 10^{-8}$	H <sub>1</sub>
Effect of plant material type	$1.72 \times 10^{-7}$	H <sub>1</sub>
Interaction between the 2 above factors	$8.29 \times 10^{-2}$	H <sub>0</sub>

\* Statistically significant threshold fixed at probability p-value 0.05.

The shapes of curves in Figures 1 and 2 lead to the following conclusions:

- 1) Leaves dry faster than stems at all temperatures (more visible at 60°C). This is probably due to their 20 to 30-fold lower thickness (see data in Table 7).
- 2) Drying rates decrease and total drying times increase with lowering temperatures, for both celery parts (see also Table 2). This is most probably caused by the higher diffusivity of water at elevated temperatures [19,12] (see Figure 5).
- 3) Drying rates decrease during time, together with the loss of moisture. Explanation relies on the fact that the fast surface water removal is predominant at process beginning, whereas towards equilibrium it is replaced by the more slower core moisture removal [11].

Findings 2) and 3) above agree with previous reports for celery leaves [19,12], slices [20] and stems [7].

The efficacy of each drying process can be assessed not only by the length of the total drying time necessary to reach constant sample masses (equilibrium), but also by the values of final humidities (translates into moisture loss). Both are presented comparatively in Table 2 for all employed conditions. It can be observed that fresh celery stalks contain more water than leaves and that their drying leads to less dry mass (see also the corresponding experimental section). This means that more water is eliminated during the exact same drying procedure, making the drying of celery stems more energetically effective (see Figure 6).

**Table 2.** Total drying time and humidity of fresh and dried celery leaves and stalks.

Drying $q$ ( $^{\circ}\text{C}$ )	Total drying time (min)	Humidity (% m/m)	
		Leaf	Stem
40	180	$4.69 \pm 0.16$	$1.52 \pm 0.34$
50	235	$4.74 \pm 0.54$	$1.93 \pm 0.18$
60	285	$5.62 \pm 0.31$	$2.49 \pm 0.66$
105	-	$4.89 \pm 0.28$	$1.92 \pm 0.28$
<b>Fresh plant</b>	-	$87.15 \pm 0.80$	$91.66 \pm 0.74$

Data in Table 2 prove that a slower, low temperature convective drying results in a 100% moisture loss, since retained humidity values at 40 and 50 $^{\circ}\text{C}$  are comparable with those at 105 $^{\circ}\text{C}$  (where the absolute dry mass was determined) for both leaf and stem. On the other hand, the rather forced process at 60 $^{\circ}\text{C}$  retained 14.9% more water in leaves and 29.7% more in stalks. This is undesirable because higher retained humidity can lead to plant putrefaction during storage. Table 2 also underlines the well-known fact that elevated drying temperatures shorten significantly process duration: in this case with 36.8% when going from 40 to 60 $^{\circ}\text{C}$ .

### Kinetic modeling of the drying process

Various kinetic models have been put forward in the literature for the thin-layer drying of agricultural products [7,11,12,19,20]. The theoretical ones are based on analytical solutions of various heat transfer or diffusion describing equations for some simple geometries, but under simplifying assumptions of an ideal drying process. Because these are rarely met, the most suitable models have proved to be either semi-theoretical or empirical [11,12].

Regardless of the equation they use to describe the time-resolved process evolution, all models rely on moisture ratio MR data *versus* total drying time  $t$ . Hence, raw kinetic information of Figures 1 and 2 was translated into such curves, by means of equation (1) to (3) (see the Experimental section). An example of MR mean values is presented in Figure 3, for data collected at 60 $^{\circ}\text{C}$  for both leaf and stem.

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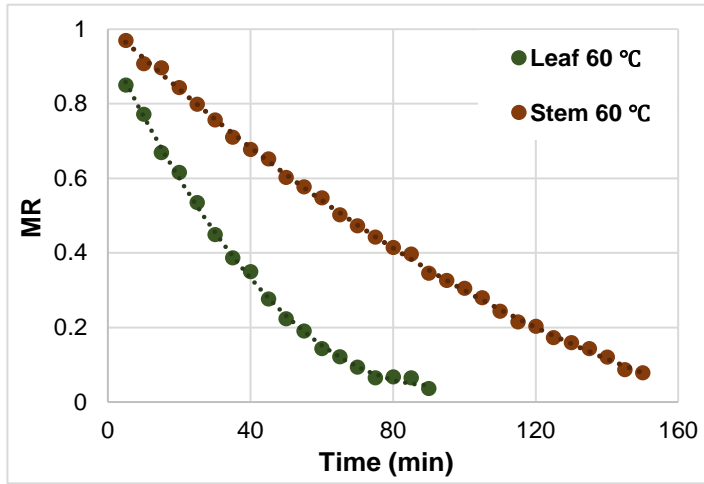


Figure 3. Moisture ratio profiles for celery leaf and stem convective drying at 60°C.

Table 3. Tested kinetic models, their equations and number of parameters  $n_{mp}$ .

Nb.	Model *	Equation	$n_{mp}$
<b>Semi-theoretical models</b>			
1	Page	$MR = \exp(-kt^n)$	2
2	Midilli & Kucuk	$MR = a \exp(-kt^n) + bt$	4
3	Two terms	$MR = a \exp(-kt) + b \exp(-k_1 t)$	4
<b>Empirical models</b>			
4	Sledz	$MR = b \exp(-kt) / (1 + a \exp(k_1 t))$	4
5	Parabolic	$MR = a + bt + ct^2$	3
6	Wang & Singh	$MR = 1 + at + bt^2$	2

\* Parameters  $k$ ,  $k_1$  and  $k_2$  stand for drying coefficients (expressed in  $\text{min}^{-1}$  if drying time is expressed in min);  $a$ ,  $b$  and  $c$  stand for equation coefficients (with dimensions depending on the model);  $n$  is a dimensionless exponent with values usually higher than 1, respectively.

Table 3 contains the list of 3 semi-theoretical and 3 empirical kinetic models chosen for testing on all MR vs time curves. The first 4 models were chosen because they have been previously found to describe drying kinetics of celery and parsley leaves, celery stalks, slices, and roots [7,12,19,20] or various other fruits, vegetables, and seeds [11]. The last 2 were selected because of their simplicity and universal application in various physical and/or chemical parameter descriptions.

The Page model derives from the Newton's law of cooling and assumes that the moisture loss in air for agricultural products is similar to the heat loss of a body immersed in cold fluid [11]. On the other hand, both the Midilli & Kucuk and the two-term model derive from the analytical solution of the Fick's second law of diffusion [11]. The Sledz model is a more recently introduced empirical model [21,22], the parabolic one is a simple quadratic equation, whereas the Wang & Singh simplifies the latter by considering the free term equal to 1 [12].

**Table 4.** Values of statistical parameters indicating kinetic model predicting quality.

Model *	$\theta$ (°C)	n <sub>obs</sub>	R <sup>2</sup> <sub>adj</sub>	RMSE	HYBRID
<i>Leaf</i>					
Midilli & Kucuk	40	40	0.9962	0.0166	0.0731
	50	36	0.9969	0.0144	0.1720
	60	18	0.9982	0.0113	0.0797
Sledz	40	40	0.9954	0.0182	0.1015
	50	36	0.9969	0.0144	6.1039
	60	18	0.9985	0.0103	0.0719
Parabolic	40	40	0.9957	0.0177	0.0793
	50	36	0.9941	0.0198	0.3797
	60	18	0.9985	0.0102	0.0724
<i>Stem</i>					
Midilli & Kucuk	40	54	0.9973	0.0140	0.1505
	50	40	0.9955	0.0185	0.1212
	60	30	0.9992	0.0076	0.0175
Sledz	40	54	0.9974	0.0139	0.1831
	50	40	0.9977	0.0133	0.0867
	60	30	0.9991	0.088	0.0230
Parabolic	40	54	0.9972	0.0144	0.1596
	50	40	0.9968	0.0155	0.0591
	60	30	0.9992	0.0077	0.0169

\* Only best fits are presented.

The suitability of each tested model to describe drying kinetics was decided upon the simultaneous satisfaction of 3 statistical model quality criteria: adjusted determination coefficient (R<sup>2</sup><sub>adj</sub>) closest to 1 and both root mean

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square error (RMSE), and hybrid fractional error deviation (HYBRID) closest to zero – see equations (7) to (9). All consider the number of observations of individual kinetic curves ( $n_{obs}$ ), as well as the number of parameters of each model ( $n_{mp}$ ). As such, results based on different  $n_{obs}$  and  $n_{mp}$  are normalized and the 6 models in Table 3 have a uniform base of comparison.

Three out of 6 tested models presented both best, and comparable results: the Midilli & Kucuk, the Sledz and the parabolic models, respectively. Table 4 summarizes the values of statistical parameters which prove the good prediction quality of these. The differences among model performances are practically insignificant and each could serve as drying kinetics behaviour predictor. These results agree with previous reports indicating the Midilli & Kucuk equation as best for celery [19] and coriander leaves [23]. The Sledz equation is also mentioned for celery leaves [19]. On the other hand, drying of celery roots [1], stem [7] and slices [20] was previously best fitted by the Page model. Yet, in this case the Midilli & Kucuk one proves to be the best fit.

However, the authors have decided for the empirical parabolic model as the best drying kinetics descriptor of both celery leaves and stalks. The reasoning is based on the simplicity of the quadratic equation as well as on the very good values of its quality indicators in Table 4. Hence, the corresponding kinetic parameters are presented in Table 5 for all employed experimental conditions.

**Table 5.** Drying kinetic parameter values of the parabolic model.

$\theta$ (°C)	a	$(-1 \times 10^3) \times b$ (min <sup>-1</sup> )	$10^5 \times c$ (min <sup>-2</sup> )
<i>Leaf</i>			
40	0.987 ± 0.009	7.57 ± 0.20	1.49 ± 0.09
50	0.947 ± 0.010	9.20 ± 0.26	2.41 ± 0.14
60	0.954 ± 0.008	19.89 ± 0.39	10.87 ± 0.40
<i>Stem</i>			
40	0.974 ± 0.006	4.07 ± 0.10	0.23 ± 0.04
50	1.018 ± 0.008	5.30 ± 0.17	0.31 ± 0.08
60	1.009 ± 0.004	8.88 ± 0.13	1.78 ± 0.08

It can be observed from Table 5 that all free term values are very close to 1, hence the Wang & Singh equation would also have been a very good fit. Parameter b values are all negative and decreasing at higher temperatures, whereas parameter c values are positive and increase in direct relation with temperature. This measurable temperature dependence is sustained by the findings of the ANOVA tests (see Table 1). Moreover, it follows a typical exponential relationship of Arrhenius type and permits the calculus of some “apparent activation energies” with correlation coefficients from 0.8828 to 0.9075. These have no physical meaning; they simply express a temperature effect. The values are presented in Table 6 and prove a stronger temperature dependence of equation coefficient b as compared to a in the parabolic model.

**Table 6.** Apparent activation energies for equation coefficients a and b of the parabolic kinetic model.

Type of plant material	Apparent activation energy * (KJ/mole)	
	Parameter a	Parameter b
<i>Leaf</i>	41.58	82.67
<i>Stem</i>	33.68	87.51

\* Has no physical meaning; it is a way to estimate the temperature dependence of parabolic model coefficients a and b.

### Drying parameters

According to equation (4), the slopes of  $\ln(MR)$  versus drying time plots are used to estimate effective water diffusion coefficient  $D_{\text{eff}}$  values. An example is presented for both leaf and stem at 60°C, in Figure 4, for data in Figure 3. Only linear portions are presented, but they cover for all employed temperatures 3 successive half-times for leaves and 2 for stalks, respectively. In other words, the linear dependence described by equation (4) is valid for at least 87.5% of process advance in the case of leaves, and for at least 75% for stem.

Towards the equilibrium (end of drying process at high times), the plots tend to curve down, more so in the case of stem. This curvature was also reported in the literature [19] and explained by the variations in the thickness of pieces subjected to drying. This reasoning agrees with the present observations since the strong variations in the stem's thickness are obvious from Figure 7 and Table 7.

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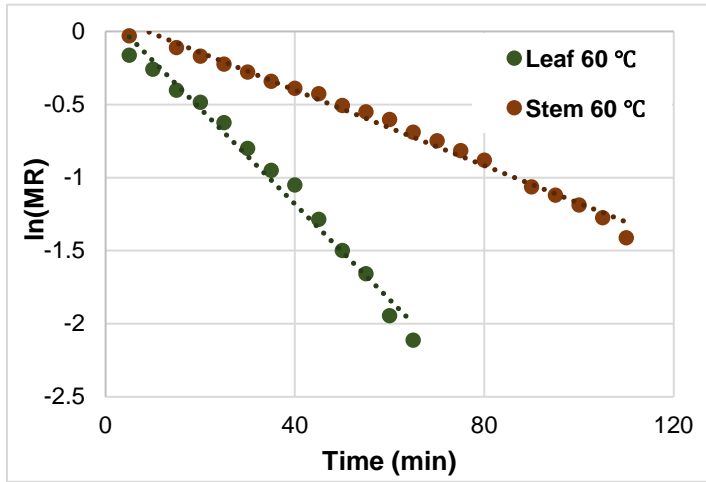


Figure 4.  $\ln(MR)$  versus drying time plots corresponding to data in Figure 3.

Figure 5 presents the calculated  $D_{eff}$  values for celery leaf and stem as a function of drying temperature. Water diffusivity proves to be 3 orders of magnitude higher for stem (values of  $10^{-9}$  order of magnitude as compared to  $10^{-12}$  for leaf), probably due to its different microstructure. Similar orders of magnitude have been reported in the literature in the case of convective drying:  $10^{-12}$  [12] to  $10^{-10}$  [19] for celery leaves, and  $10^{-10}$  for basil [22], respectively.

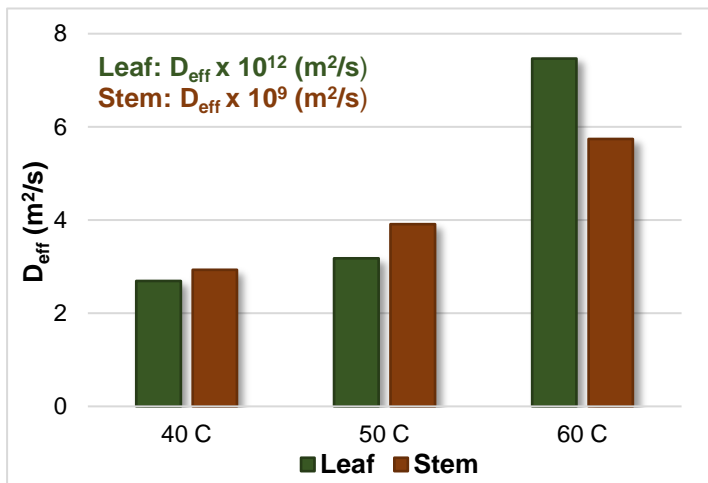


Figure 5. Values of effective water diffusivity ( $D_{eff}$  values are of  $10^{-12}$  and  $10^{-9}$  order of magnitude for leaf and stem, respectively).

Water diffusivity increases with temperature and  $D_{\text{eff}}$  values in Figure 5 served for the determination of drying activation energy, by means of equation (5). An average value of 44.01 KJ/mole of removed water was obtained for leaves, and of 29.02 KJ/mole for stalks (with corresponding correlation coefficients of 0.8575 and 0.9902), respectively. These values show that the moisture loss occurs more easily and is less temperature dependent for celery stem than for leaf. They agree with previous findings, for example 36.09 [12] and 31.72 KJ/mole [19], respectively, for celery leaves [12]. Convective drying of many other fruits and vegetables, although carried out under different conditions, also exhibits comparable values [12].

The specific energy consumption SEC was computed, for both leaves and stalks, by dividing the total amount of consumed energy during drying with the mass of removed water – see equation (6). Its values are illustrated in Figure 6 and agree with previous reports for the convective drying of celery [12].

Results indicate that drying of celery leaves is approximately twice as energy demanding than that of stalks, even under identical process conditions. This finding agrees with their 3 orders of magnitude lower water diffusivity coefficient, as well as with their 34% higher drying activation energy (see Figure 5). The use of an elevated temperature leads to a more energetically efficient process, due to a significantly shorter drying time (see Table 2) and better water diffusivity (see Figure 5).

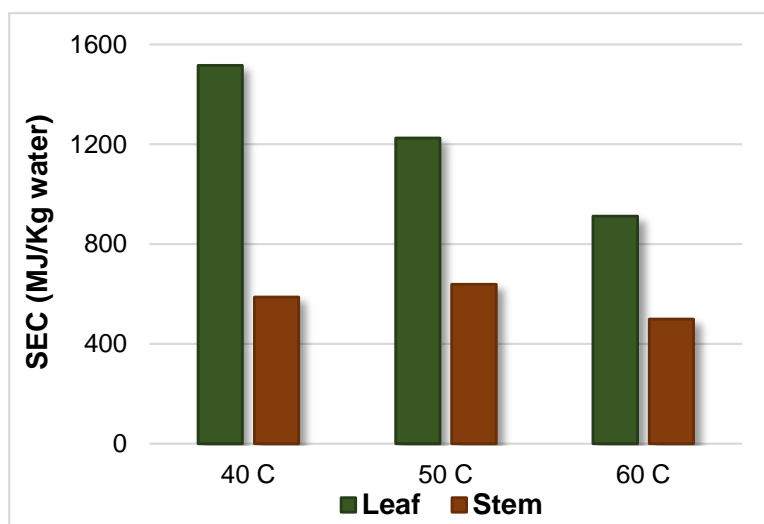


Figure 6. Values of specific energy consumption.

## CONCLUSIONS

Despite the wide use of forced convective drying for various fruits and vegetables, there is a lack of systematic studies at mid-range temperature, as well as process comparison for various useful parts of the same plant when dried under identical conditions. Hence, this work focused on the comparative description of thin-layer drying of celery leaves and stalks (industrially often dried together) at 40, 50 and 60°C, respectively.

Gravimetric measurements were used to obtain time-resolved data under all employed conditions. The procedure resulted in almost 100% moisture loss for both celery leaf and stem, regardless of employed temperature. However, drying of leaves is somewhat faster. A total of 6 semi-theoretical and empirical models were tested for their best suitability with kinetic behavior, by means of 3 statistical parameters as indicators of model prediction quality. The Midilli & Kucuk, Sledz and parabolic equations showed best but comparable performances. Yet, because of its simplicity, the empirical parabolic model was chosen to describe the drying kinetics of both celery leaves and stalks.

Mono- and bi-factorial ANOVA tests were used to prove that both independent operating parameters (temperature and type of plant material) affect the evolution of the process in a statistically significant manner, but that they do not interact. Hence, the calculated drying parameters were consistent with these observations. For example, 2 out of 3 equation coefficients of the chosen kinetic model are temperature affected and permit quantification of the respective dependence.

Effective water diffusivity coefficients were also temperature dependent for both employed plant parts, but 3 orders of magnitude higher for stalks. Hence, their drying activation energy was 34% lower. These values correlate with the calculated specific energy consumption and drying of stems proved to be more energy efficient than that of leaves.

## EXPERIMENTAL SECTION

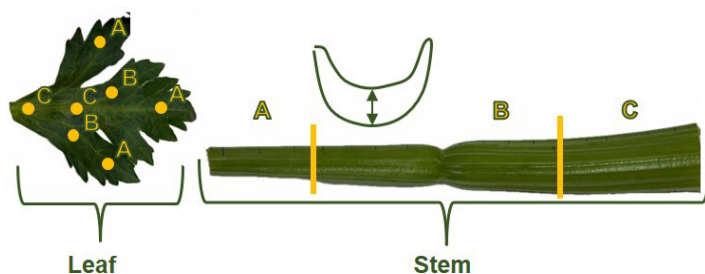
### Preparation of characterization of celery samples

Fresh and leaf rich celery stalks with no roots were purchased from a local market. The ones lacking visible defects and with a uniform appearance were kept for experimental use. Leaves and stems were separated, washed under tap water, and air-dried for 30 min on paper towels at room temperature. Further, the vegetal material was cut in approximately 1x1 cm pieces, as shown in Figure 6.



**Figure 6.** Example of celery leaf and stalk pieces prepared for drying.

Leaf and stalk *thickness* measurements were performed in 3 different regions (A, B and C, respectively), as depicted in Figure 7, and according to the morphological particularities of the plant parts. A calliper (YATO, TOYA S.A., Wroclaw, Poland) was used for this purpose. The results are presented in Table 7.



**Figure 7.** Thickness measurement points/regions for celery leaves and stalks.

The *humidity* (% m/m) of fresh and dried celery was determined with an infrared moisture analyser (Model MA 50.X2.IC.A., Radwag, Poland); 1 g samples were heated by means of IR radiation at 105°C until reaching constant mass.

**Table 7.** Thickness values of celery leaves and stalks.

Thickness (mm)	Point A	Point B	Point C	Mean value*
Leaf	0.245 ± 0.053	0.383 ± 0.041	0.475 ± 0.050	0.368 ± 0.116
Stem	6.125 ± 0.427	7.950 ± 1.476	10.600 ± 0.126	8.225 ± 2.250

\* Refers to the average of the measurements in points A, B and C, respectively.

## Drying procedure

Samples of 10 g of either leaf or stalk pieces were placed in parchment paper trays and subjected to drying on the middle grid of an electrical oven (HB-8053NG, Hausberg, Ergene, Turkey) with ventilation. Temperatures of 40, 50, 60, and 105°C, respectively, were employed.

The process' evolution at 40, 50 and 60°C was monitored gravimetrically, every 5 min, until the mass of each individual sample remained constant for at least 3 successive determinations. Mass measurements were carried out with a 0.01 g accuracy digital analytical balance (Model AXE, KERN & SOHN GmbH, Balingen, Germany).

Besides the electronic setting of temperature, its actual value inside the oven was monitored with a laboratory thermometer ranged 0 to 150°C. The air flow hit the samples vertically, from both above and below, at a velocity of  $(4.16 \pm 0.22)$  m/s. The latter was measured in 12 points, with a digital hand anemometer (Model JV796255, NJTY, Guangdong, China).

All kinetic measurements were carried out in triplicate, except the ones at 60°C, which had 6 repetitions, for both leaves and stem. Drying time at 105°C took 24 hours (triplicate) and finalized with one mass measurement each.

## Calculus of drying parameters

The moisture ratio MR [1,7,12,19] was calculated from each mass *versus* drying time individual measurement by means of equation (1),

$$MR = \frac{X - X_e}{X_0 - X_e} \quad (1)$$

in which  $X$ ,  $X_i$  and  $X_e$  stand for the dry base moisture content of the sample at a certain time  $t$ , at the start of the process and at its equilibrium, respectively.  $X$  values are expressed in g water / g dry base and calculated as

$$X = \frac{\text{Sample mass} - \text{Dry mass}}{\text{Dry mass}} (\text{g} / \text{g}) \quad (2)$$

for each mass measurement. The plant dry mass was determined after drying 10 g at 105°C for 24 hours, to be equal to  $(1.97 \pm 0.06)$  g and  $(0.75 \pm 0.09)$  g, for leaf and stem samples, respectively. Because of constant 10 g initial mass samples, the values of  $X_0$  are constant and equal to 4.085 g/g and 12.333 g/g, for leaf and stem, respectively. On the other hand, the values of  $X_e$  differ for each set of kinetic measurements, in agreement with the final stable sample mass recorded at process equilibrium.

A combination of equations (1) and (2) leads to an MR value expressed simply as a function of mass measurements, as follows:

$$MR = \frac{\text{Momentary mass} - \text{Equilibrium mass}}{\text{Initial mass} - \text{Equilibrium mass}} \quad (3)$$

The effective water diffusion coefficient  $D_{\text{eff}}$  ( $\text{m}^2/\text{s}$ ) was determined from the slope of  $\ln(\text{MR})$  versus drying time graphs [12,19,21,22], according to:

$$\ln(\text{MR}) = \ln \frac{m - m_e}{m_0 - m_e} - \frac{\rho^2 D_{\text{eff}} t}{4L^2} \quad (4)$$

where  $L$  stands for the half-thickness of the material subjected to drying (m). Its value was considered equal to the half of the last column values in Table 7 (since moisture loss occurs from all sides of the plant pieces).

The activation energy  $E_a$  (KJ/mole evaporated water) was calculated from the temperature dependence of  $D_{\text{eff}}$  values, described as:

$$D_{\text{eff}} = D_0 \exp \left( -\frac{E_a}{RT} \right) \quad (5)$$

where  $D_0$  ( $\text{m}^2/\text{s}$ ) stands for a pre-exponential factor,  $T$  (K) for temperature and  $R$  for the universal gas constant, respectively.

The specific energy consumption SEC (J/Kg removed water) [12,22] was computed by:

$$SEC = \frac{TT}{m_s (X_0 - X_e)} E \quad (6)$$

where  $TT$  stands for the total drying time (s),  $E$  (equalling 2225 W) is an oven characteristic, and  $m_s$  (Kg) represents the dried solid matter at equilibrium, respectively. Variables  $m_s$  and  $X_i$  have individual values for each kinetic curve, whereas  $X_0$  is constant (see above).

### Calculus of statistical parameters

The following statistical indicators were calculated for each kinetic curve: the adjusted determination coefficient  $R^2_{\text{adj}}$ , the root mean square error RMSE, and the hybrid fractional error deviation HYBRID, respectively [12,19,24,25]. Their respective formulas are given in equations (7) to (9).

$$R^2_{\text{adj}} = 1 - (1 - R^2) \frac{(n_{\text{obs}} - 1)}{(n_{\text{obs}} - n_{\text{mp}} - 1)} \quad (7)$$

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$$RMSE = \sqrt{\frac{\sum_{i=1}^{n_{obs}} (MR_{exp} - MR_{calc})_i^2}{n_{obs}}} \quad (8)$$

$$HYBRID = \frac{100}{n_{obs} - n_{mp}} \frac{\sum_{i=1}^{n_{obs}} \left( \frac{MR_{exp} - MR_{calc}}{MR_{exp}} \right)_i^2}{\sum_{i=1}^{n_{obs}} \left( \frac{MR_{exp} - MR_{calc}}{MR_{exp}} \right)_i} \quad (9)$$

In equation (7),  $R^2$  stands for the correlation coefficient of the model. In equations (8) and (9),  $MR_{exp}$  and  $MR_{calc}$  stand for the experimental and model calculated moisture ratios, respectively. The variable  $n_{obs}$  equals the number of experimental observations in a kinetic curve, whereas  $n_{mp}$  the parameter number of a tested model. The values of  $R^2_{adj}$  and RMSE were generated automatically during model fitting, while the HYBRID value was calculated by hand for each tested model.

### Employed software

Statistical mono- and bi-factorial ANOVA analysis was carried out with the “*Data Analysis*” tool of Microsoft Excel for Microsoft 365 (Microsoft Corporation, Redmond, WA, USA).

Kinetic curve fittings and model parameter calculus were performed with the “*Nonlinear Curve Fit*” module of Origin 2018, Version 95E (OriginLab Corporation, Northampton, MA, USA).

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