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# STUDIES ON THE DRYING KINETICS OF CELERY PURÉE UNDER CONTROLLED TEMPERATURE CONDITIONS USING A HALOGEN MOISTURE ANALYZER

BY

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**Abstract.** This study investigates the drying kinetics of celery purée (*Apium graveolens L.*) using a halogen moisture analyzer at isothermal temperatures ranging from 50 to 105°C. Thermogravimetric analysis (TG/DTG/DTA) revealed an initial moisture content of 88.67% and characteristic thermal degradation of hemicellulose, cellulose, and lignin. Thin-layer drying curves were obtained, and effective moisture diffusion coefficients increased with temperature, ranging from $4.083 \cdot 10^{-10}$ to $20.511 \cdot 10^{-10}$ $m^2/s$. Activation energy for moisture diffusion, calculated using the Arrhenius equation, was 30.18 kJ/mol, comparable to literature values reported for celery slices. Results indicate similar moisture diffusion mechanisms despite structural differences between purée and intact plant tissues. The study provides valuable experimental data for optimizing drying processes, reducing energy consumption, and producing high-quality dehydrated vegetable products with potential industrial applications.

**Keywords:** celery purée, drying kinetics, halogen moisture analyzer, effective moisture diffusion, activation energy.

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## 1. Introduction

Drying of fruits and vegetables is a complex, energy- and time-consuming operation, yet it is essential for extending product shelf life and reducing handling, packaging, and transportation costs by decreasing product volume and weight. Although drying is one of the oldest and most important preservation methods, experimental practices conducted in isolation, without correlation to mathematical modeling tools, may negatively affect process efficiency and the quality of the final product (Mujumdar, 2014; Mohammed *et al.*, 2024).

Studies on the evaluation of drying kinetics and the assessment of energy consumption are very important in the field of fruit and vegetable drying (Erbay and Icier, 2010). Drying behavior is often investigated through thin-layer drying, a method widely used in laboratory experiments, as it simplifies the analysis of heat and mass transfer mechanisms and enables the development of reliable predictive models (Doymaz, 2011).

Numerous recent studies have examined the drying of horticultural products, including celery (*Apium graveolens L.*), highlighting the influence of temperature on drying kinetics, the effective moisture diffusion coefficient, and activation energy (Nasfi and Romdhane, 2025; Mouhoubi *et al.*, 2019). However, most existing research focuses on intact plant material, such as celery leaves (Nasfi and Romdhane, 2025) or root pieces (Białobrzewski and Markowski, 2004) using conventional convective drying methods (Wei *et al.*, 2015; Kręcisz *et al.*, 2023) or other emerging drying techniques (Kutlu, 2025; Rudy *et al.*, 2024; Jezek *et al.*, 2008). There are no studies that evaluate the drying of celery purée.

The present study focuses on applying these principles to the drying of celery purée. Compared to intact plant material, vegetable purées exhibit a homogenized structure that significantly influences heat and mass transfer mechanisms and results in distinct drying behavior, thus requiring a specific experimental approach (Zielinska and Michalska, 2016). The importance of understanding the engineering aspects of drying is further emphasized by the high energy consumption associated with this operation in the food industry.

Although conventional technologies, such as open sun drying (OSD), remain popular due to their simplicity, they present major disadvantages, including contamination risks, lack of process parameter control, and prolonged drying times, which may compromise the safety and quality of the final product (Kumar *et al.*, 2014; Rajesh *et al.*, 2024).

In this context, the use of modern laboratory equipment, such as halogen moisture analysers, provides an efficient alternative for studying drying kinetics under strictly controlled conditions. These devices allow precise temperature regulation and continuous monitoring of mass loss, facilitating the rapid and reproducible acquisition of drying kinetic curves (Mettler Toledo, 2015).

The scientific novelty of the present study lies in the investigation of the drying kinetics of celery purée (*Apium graveolens L.*), a homogenized plant material whose mass transfer mechanisms differ significantly from those of intact plant tissues and which remains insufficiently explored in the scientific literature. Unlike existing studies that predominantly focus on drying celery leaves or root pieces using conventional convective methods, this research employs a halogen moisture analyzer to ensure strictly controlled temperature conditions and continuous mass loss monitoring. The main contribution of this work consists of obtaining and mathematically modeling thin-layer drying kinetic curves for celery purée, providing relevant experimental data for optimizing drying processes, reducing energy consumption, and developing high-quality dehydrated plant-based products with potential industrial applications.

This study aims to explore the mathematical modeling of celery purée drying kinetics using the thin-layer method under controlled temperature conditions with a halogen moisture analyzer, in order to optimize the drying process, reduce energy consumption, and ensure a superior-quality final product.

## 2. Materials and methods

The research aims to analyze the drying process under a controlled air atmosphere, to determine drying curves and effective diffusion coefficients, as well as the activation energy, using a halogen heating source analyzer. In addition, the thermal stability and the initial amount of moisture of celery purée was evaluated by applying dynamic thermal analysis (TG, DTG, DTA), and thermogravimetric data were processed using STAR$^e$ software. Thus, for the present study, fresh celery roots were purchased on the local market in Iasi city, were used. Slices were cut from the celery root and subsequently processed in a blender until a purée consistency was obtained, from which samples were taken and analyzed using a Mettler Toledo TGA-SDTA851$^e$ instrument, in an air atmosphere under dynamic conditions, with a flow rate of 20 mL/min, a heating rate of 10°C/min, over a temperature range of 25–700°C, and a sample mass of 9.8472 mg.

The kinetic study of drying celery samples under isothermal conditions (50, 60, 70, 80, 90, and 105°C) was carried out using a Mettler Toledo HG63 instrument in an air atmosphere, with sample masses 30.29±0.26 g. The thickness of celery purée layer initially coincided with the height of the tray used for the experiment, namely $7 \cdot 10^{-3}$ m. The diameter of the tray used in the experimental determinations is 0.094 m. To verify the reproducibility of the results obtained at a temperature of 70ºC, two tests were conducted.

## 3. Results and discussions

The thermogravimetric (TG), derivative thermogravimetric (DTG), and differential thermal analysis (DTA) curves recorded for the celery purée sample are presented in Fig. 1.

The main thermogravimetric characteristics are presented in Table 1. The obtained results show that the moisture level of the analyzed celery sample is 88.67%. This value is in full agreement with other reports in the literature regarding the moisture content of celery root (Kutlu, 2025). At temperatures above 232°C, thermal decomposition occurs in two stages, with the temperatures at which the reaction rates are maximal at 259°C and 527°C, respectively. At 700°C, a small amount of residue remains, amounting to 4.39%. During these stages, the decomposition of hemicellulose, cellulose, and lignin occurs (Filip *et al.*, 2024).

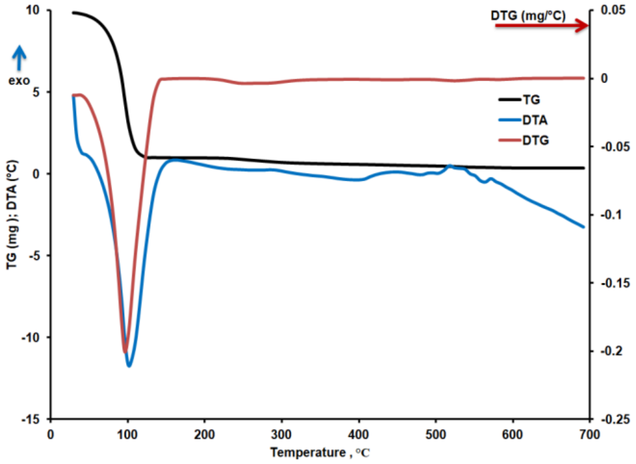

Fig. 1 − Thermogravimetric curves.

**Table 1**

*Thermogravimetric characteristics of celery purée*

| Stage | I | II | III |
|---|---|---|---|
| $T_{onset}$, ºC | 63 | 232 | 512 |
| $T_{peak}$, ºC | 98 | 259 | 527 |
| $T_{endset}$, ºC | 116 | 309 | 554 |
| W, % | 89.29 | 4.46 | 1.88 |
| DTA characteristics | endo | exo | exo |
| Residue, % | 4.39 | | |

Using the Mettler Toledo HG63 equipment, experimental determinations of moisture loss over time were carried out for celery puree under constant temperature conditions: 50, 60, 70, 80, 90, and 105°C. Based on these determinations, drying curves (moisture content–drying time) were plotted, as presented in Fig. 2. For the temperature of 70ºC, two determinations were carried out, yielding very similar results. The moisture ratio (MR) was calculated using Equation (1), in which $M_0$ represents the initial moisture content of the sample, $M_e$ represents the equilibrium moisture content determined from the drying curves at the point when the sample mass no longer changes with increasing time, and M is the moisture content of the sample at any given time t.

$$MR = \frac{M-M_e}{M_0-M_e} \tag{1}$$

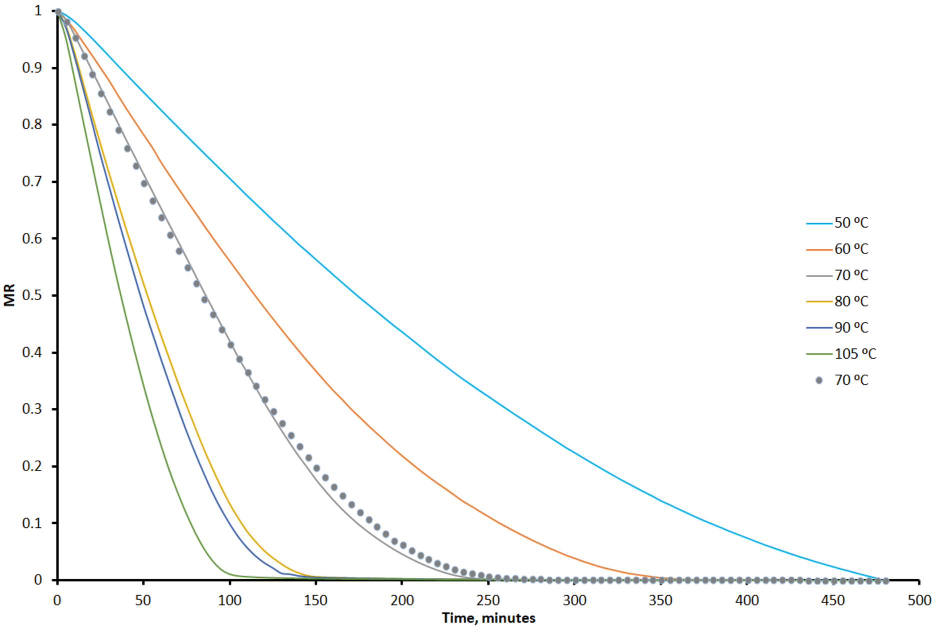

Fig. 2 − Drying curves (moisture content–time) at different temperatures.

To highlight the stages of the drying process, based on the experimental data obtained at the six temperatures, the drying rate (kg moisture/m²·s) was calculated. The resulting values were graphically represented in Fig. 3 as a function of moisture content, u (kg moisture/kg initial sample). As expected, the drying rate increases with increasing temperature. Furthermore, the maximum moisture content of the celery puree is identical to that determined by thermogravimetric analysis using the Mettler Toledo TGA-SDTA851$^e$ equipment.

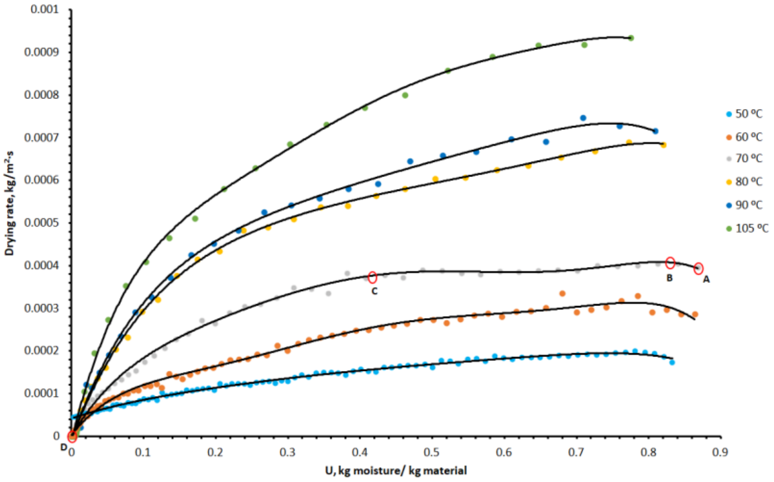

Fig. 3 − Drying curves (drying rate–moisture content) at different temperatures.

By analyzing the results presented in Fig. 3, the presence of the following drying periods can be observed: the heating-up period (AB), the constant-rate drying period (BC), and the falling-rate drying period (CD). At low temperatures, the longest period is the constant-rate drying period, also referred to as the actual drying period. If the drying conditions do not change, the evaporation rate for the celery purée samples subjected to analysis–and consequently the drying rate–remains constant. At temperatures higher than 70°C, it is observed that the falling-rate drying period becomes predominant.

The drying curves of celery purée at different temperatures (50–105°C) revealed a clear influence of temperature on both the overall drying time and the characteristics of the drying periods. As expected, the total drying time decreased significantly with increasing temperature. At 50°C, the moisture ratio (MR) decreased gradually, and complete drying was achieved only after approximately 450 minutes, while at 60°C, drying was completed in around 300 minutes. Further increases in temperature accelerated the process, with 70–80°C requiring 150–200 minutes, and the highest temperatures, 90 and 105°C, achieving complete drying in just 100–120 minutes.

Analysis of the drying rate curves shows that the initial heating period was relatively short at all temperatures, but the duration of the constant-rate period varied markedly. At lower temperatures (50–60°C), the constant-rate period was prolonged and represented the dominant stage of drying, reflecting a steady moisture removal as water evaporated from the surface. In contrast, at higher temperatures (90–105°C), this period was extremely short or nearly absent, and the drying process was rapidly dominated by the falling-rate period, where moisture removal depends on internal diffusion. At these elevated temperatures, the mass transfer mechanism is predominantly governed by internal moisture diffusion within the material matrix, as characterized by the effective diffusion coefficient ($D_{eff}$). An increase in temperature enhances the mobility of water molecules and reduces internal mass transfer resistances, resulting in higher values of the diffusion coefficient.

The results indicate that higher temperatures increase the initial drying rate and shorten the constant-rate period, accelerating the overall drying process. Higher values of the effective diffusion coefficient at elevated temperatures account for the significant reduction in total drying time and the predominance of the falling-rate drying period, during which the migration of moisture from the interior toward the surface becomes the rate-limiting step of the process. The variation of the diffusion coefficient with temperature can be described by an Arrhenius-type relationship, suggesting the presence of an activation energy associated with the moisture diffusion process. Higher temperatures reduce the energy barrier required for the movement of water molecules, thereby promoting the acceleration of the drying process. However, the predominance of the falling-rate period at high temperatures also suggests that care must be taken to ensure uniform moisture removal, especially in thicker layers of purée. At very high temperatures, pronounced moisture gradients, structural shrinkage, or the formation of a surface crust may occur; these phenomena can hinder the subsequent diffusion of moisture from the interior and adversely affect the final product quality. Therefore, an optimal drying temperature should balance drying speed and product quality, preventing uneven dehydration or thermal degradation of sensitive components, taking into account the variation of the diffusion coefficient and the internal mass transfer mechanisms involved in the drying process.

Taking into account the analytical solution of Fick's equation for different geometrical shapes (Royen, 2020), namely the "thin plate" case developed by Crank (Crank, 1975), and assuming that moisture transport occurs by diffusion while temperature and diffusion coefficients remain constant, the effective diffusion coefficients ($D_{eff}$) can be determined from the following relationship for long solvent removal times (Equation 2):

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 \cdot D_{eff} \cdot t}{\delta^2} \tag{2}$$

where δ is the thickness of the analyzed celery sample. From the graphical representation, straight lines with negative slopes were obtained, with correlation coefficients higher than 0.91. Table 2 presents the correlation coefficients ($R^2$), the thickness of the the celery purée samples placed in the crucible (δ), and the values of the effective diffusion coefficients ($D_{eff}$). In Table 2 are presented the correlation coefficients ($R^2$), the thickness of the celery purée sample placed in the crucible (δ), and the values of the effective diffusion coefficients ($D_{eff}$). In a recent study, Kurt et al. reported, for the convective drying of celery root pieces, effective diffusion coefficients of $1.701 \cdot 10^{-10}$ and $3.317 \cdot 10^{-10}$ $m^2/s$ for temperatures ranging from 55 to 75°C (Kurt *et al.*, 2025). In the same study, for the infrared drying of celery root pieces, the authors reported higher diffusion coefficients within the same temperature range, between $2.746 \cdot 10^{-10}$ and $4.987 \cdot 10^{-10}$ $m^2/s$. Using the Mettler Toledo HG63 equipment, which employs halogen drying technology, our study obtained slightly higher values of the diffusion coefficients, considering that celery purée was used in the drying process. This behavior is due to the fact that, in materials with a colloidal capillary–porous structure (such as celery root), the effective diffusion coefficient of water depends not only on temperature and moisture content, but also on material density (Białobrzewski and Markowski, 2004).

Based on the values of the effective diffusion coefficients at different temperatures, the logarithmic form of the Arrhenius equation, Equation (3), was applied. From the graphical representation of ln $D_{eff}$ as a function of 1/T, the activation energy was determined, and its value is presented in Table 2.

$$\ln(D_{eff}) = ln(D_0) - \frac{Ea}{RT} \quad (3)$$

**Table 2**

*Effective diffusion coefficients and activation energy*

| Temperature °C | $R^2$ | $\delta \cdot 10^3$(m) thickness of the layer | $D_{eff} \cdot 10^{10}$ ($m^2$/s) | $\ln D_0$ | Ea (kJ/mol) |
|---|---|---|---|---|---|
| 50 | 0.986 | 7 | 4.083 | -10.366 | 30.18 |
| 60 | 0.979 | | 7.804 | | |
| 70 | 0.979 | | 8.288 | | |
| 80 | 0.980 | | 14.525 | | |
| 90 | 0.984 | | 15.272 | | |
| 105 | 0.983 | | 20.511 | | |

The activation energy obtained in this study for the drying of celery purée was 30.18 kJ/mol, a value comparable to that reported in the literature (Kurt *et al.*, 2025) for the conventional drying of celery in sliced form (control group), where the activation energy was 31.66 kJ/mol. The small difference indicates similar moisture diffusion mechanisms, despite differences in the material structure.

## 3. Conclusions

Thermogravimetric analysis of celery purée confirmed a high initial moisture content (88.67%) and revealed distinct thermal degradation stages associated with hemicellulose, cellulose, and lignin, indicating adequate thermal stability within the investigated drying temperature range. Drying kinetics were strongly influenced by temperature, with higher temperatures significantly reducing drying time and increasing the moisture evaporation rate. The process exhibited three characteristic stages–heating, constant-rate drying, and falling-rate drying–the latter becoming predominant at temperatures above 70°C. Effective moisture diffusion coefficients increased with temperature, showing slightly higher values than those reported for celery slices due to the homogenized structure of the purée. The activation energy for moisture diffusion was 30.18 kJ/mol, close to literature values, indicating similar diffusion mechanisms. The study demonstrates that halogen moisture analyzers enable rapid and reproducible acquisition of drying data, providing valuable information for optimizing drying processes, reducing energy consumption, and producing high-quality dehydrated vegetable products. Future research could explore the influence of alternative drying technologies, such as infrared or microwave-assisted drying, the effect of different purée consistencies on mass transfer, and the scaling-up of drying processes for industrial applications.

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# STUDIUL CINETICII USCĂRII PIUREULUI DE ȚELINĂ ÎN CONDIȚII DE TEMPERATURĂ CONTROLATĂ UTILIZÂND UN ANALIZOR DE UMIDITATE CU HALOGEN

## (Rezumat)

Acest studiu investighează cinetica de uscare a piureului de țelină (*Apium graveolens L.*) utilizând un analizor de umiditate cu halogen, la temperaturi izoterme de 50–105°C. Analiza termogravimetrică (TG/DTG/DTA) a arătat un conținut inițial de umiditate de 88,67% și etape caracteristice de degradare a hemicelulozei, celulozei și ligninei. Curbele de uscare în strat subțire au fost obținute și analizate, iar coeficienții efectivi de difuzie a umidității au crescut odată cu temperatura ($4,083 \cdot 10^{-10}$ – $20,511 \cdot 10^{-10}$ $m^2/s$). Energia de activare a difuziei a fost determinată prin ecuația Arrhenius și a fost de 30,18 kJ/mol, comparabilă cu valorile raportate pentru felii de țelină. Rezultatele indică mecanisme similare de difuzie a umidității, în ciuda diferențelor structurale dintre piure și țesuturile intacte. Studiul furnizează date valoroase pentru optimizarea uscării, reducerea consumului de energie și obținerea de produse vegetale deshidratate de calitate superioară.