

Mathematical Modelling, Drying Kinetics, and Moisture Diffusion Behaviour of Leek Leaves (*Allium ampeloprasum* var. *porrum*) during Hot-Air Oven Drying

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ABSTRACT

This study investigated the drying kinetics, mathematical modelling, and moisture diffusion behaviour of leek leaves (*Allium ampeloprasum* var. *porrum*) during hot-air oven drying at 45, 55, and 65 °C. The study aimed to identify the most suitable thin-layer drying model and determine the effective moisture diffusivity and activation energy of leek leaves. Drying occurred entirely in the falling-rate period, which indicates that internal diffusion controlled moisture removal. Among the evaluated models, the cubic model gave the best fit at 45 °C, with an R^2 of 98.96%, root mean square error (RMSE) of 0.053, and sum of squared errors (SSE) of 0.0593. The Wang and Singh model gave the best fit at 55 °C and 65 °C, with R^2 values of 92.26% and 93.17%, RMSE values of 0.078 and 0.102, and SSE values of 0.0874 and 0.1140, respectively. Effective moisture diffusivity increased from 9.13×10^{-9} m²/s at 45 °C to 31.69×10^{-9} m²/s at 55 °C and 43.36×10^{-9} m²/s at 65 °C. The activation energy reached 70.08 kJ/mol, showing the temperature sensitivity of moisture migration in leek tissue. These findings provide useful kinetic parameters for selecting drying conditions and improving predictive modelling in small-scale and industrial leek drying processes. This study contributes part-specific drying data for the green leaf portion of leek, which remains less represented than whole-slice and pseudo-stem drying data.

KEYWORDS

Activation energy; Drying kinetics; Effective moisture diffusivity; Mathematical modelling; Water removal

1. INTRODUCTION

Leek (*Allium ampeloprasum* var. *porrum*) is an economically significant vegetable in Indonesia, cultivated primarily for its elongated, cylindrical pseudo-stem formed by blanched leaf sheaths. In 2023, national production reached approximately 639,675 tons, with an average productivity of 6.26 tons per hectare [1], [2]. The distinctive aroma and taste of leeks arise from sulphur-containing compounds, which are responsible not only for their pungency but also for their recognized biological activities, including antioxidant and antimicrobial properties [3]. Beyond their culinary relevance, recent evidence identifies leeks as a potential functional food associated with the prevention of several chronic diseases. Epidemiological and clinical studies have linked the consumption of *Allium* species with reduced risks of cardiovascular disorders and certain cancers, particularly breast cancer [4]. These protective effects are attributed to bioactive constituents such as flavonoids, polyphenols, and saponins, which possess antioxidant, anti-inflammatory, hypolipidemic, and antihypertensive activities [5]. However, like many leafy vegetables, leeks are highly perishable due to their high moisture content, resulting in short shelf life

and limited post-harvest distribution [6]. To minimize losses while preserving nutritional quality, suitable and optimized drying methods are required.

Hot-air oven drying remains one of the most common thermal dehydration methods used in food and agricultural industries because of its operational simplicity and cost-effectiveness [7], [8]. It removes moisture through convective heat transfer, where heated air supplies thermal energy to the product surface, initiating water evaporation [9]. Compared with more capital-intensive techniques such as freeze-drying or vacuum drying, hot-air oven drying offers a practical option for small and medium-sized enterprises. Wei et al. (2026) [10] noted its ability to achieve target moisture levels without complex equipment, while Luis Vargas et al. (2022) [11] highlighted its effectiveness in retaining nutritional quality in selected vegetables. Nonetheless, this method has limitations, Xu et al. (2022) [12] observed that hot-air oven drying reduced color intensity and phenolic retention in chrysanthemum, and microscopic analyses revealed cellular shrinkage and structural collapse. Despite these drawbacks, hot-air oven drying continues to play a crucial role in food preservation, especially where resource constraints restrict the use of advanced technologies.

Mathematical modelling of drying behavior is essential for understanding moisture transport mechanisms and optimizing drying operations. Empirical and semi-theoretical thin-layer models are frequently used to describe the drying kinetics of vegetables, including *Allium* species. These models predict drying behavior by analyzing changes in moisture ratio over time, which is critical for process design, control, and quality evaluation [13]. In a cabinet drying study, Doymaz (2008) [14] identified the Logarithmic and Midilli models as the most suitable for leeks, yielding high coefficients of determination and low χ^2 and RMSE values. The effective moisture diffusivity ranged from 1.145×10^{-10} to 2.642×10^{-10} m²/s. Dadali & Özbek (2008) [15] extended this work using microwave drying and reported diffusivity values of 0.618×10^{-10} to 2.128×10^{-10} m²/s for the white portion and 0.256×10^{-10} to 0.611×10^{-10} m²/s for the green portion, concluding that the Midilli model provided the best fit. Activation energy derived from the Arrhenius relationship was 0.9530 W/g for the white part and 1.2045 W/g for the green leaves. These results underscore the importance of part-specific evaluation in modelling the drying of vegetables with heterogeneous structures.

This study investigates the drying kinetics and moisture diffusion behavior of leek (*Allium ampeloprasum* var. porrum) during hot-air oven drying, with a specific focus on the green leaf portion. The green leaf portion requires separate evaluation because it has a thinner structure, higher surface exposure, and different tissue composition from the white pseudo-stem. These characteristics may affect moisture movement, drying rate, and model performance. This study applies seven thin-layer drying models, namely First-order, Second-order, Cubic, Wang and Singh, Henderson and Pabis, Vega Lemus, and Logarithmic models. These models were selected because they represent commonly used empirical and semi-empirical approaches for describing nonlinear moisture-ratio changes during food drying. The main contribution of this research is the provision of part-specific drying kinetic data for the green leaf portion of leek, together with model constants, effective moisture diffusivity, and activation energy under hot-air oven drying conditions.

2. MATERIALS AND METHODS

2.1. Materials

Fresh leeks (*Allium ampeloprasum* var. porrum) were obtained from local farmers in Kaliangkrik, Magelang, Central Java, Indonesia. The study used samples at commercial maturity with uniform physical characteristics. The selected leeks showed a fresh green color typical of healthy leek leaves and had no yellowing, which indicated the absence of visible defects. Immediately after harvesting, the leeks were packed in polyethylene bags and transported to Universitas Gadjah Mada, Sleman, Yogyakarta. Upon arrival at the Process and Food Laboratory, Department of Bioresources Technology and Veterinary, the samples were stored at 4 °C in a Sharp SJC218 cold storage unit to maintain their quality before processing. Before drying, the samples were cut into slices with a thickness of 1 cm. The initial moisture content of the leek samples was $93.16 \pm 1.43\%$ on a wet basis.

2.2. Hot-Air Drying Procedure

Hot-air oven drying (HOD) was used to evaluate the moisture removal behavior of leek samples at 45, 55, and 65 °C, following the procedure described by Yin et al. (2025) [16]. The initial moisture content was determined using a Model XM50 moisture analyzer (Precisa Gravimetrics AG, Switzerland). Triplicate samples were spread evenly on aluminium dishes at a thickness of 1 cm and weighed using a Model TX423L analytical balance (Shimadzu, Japan). The samples were dried in a Memmert UN75 oven until the final moisture content reached below 10%. Constant weight was defined as a weight change of less than 1% over two consecutive measurements. During drying, the relative humidity ranged from 61 to 64%. The drying temperatures were monitored and controlled every 30 minutes to maintain the selected drying conditions. Air velocity inside the drying chamber was not measured. Therefore, the kinetic parameters reported in this study should be interpreted as apparent values under the specified oven configuration.

2.3. Mathematical Modeling of The Drying Curves

Drying kinetics were modelled by fitting the experimental moisture ratio data to seven thin-layer drying models. Approximately 3 g of prepared leek samples were dried in triplicate at 45, 55, and 65 °C. Sample weight was recorded every hour until the samples reached constant weight. Moisture content on a wet basis, moisture content on a dry basis, moisture ratio (MR), and drying rate (DR) were calculated using equations (1), (2), (3), and (4) [17], where (w_t) is the sample weight at drying time (t), (w_d) is the dry weight, (M_t) is the moisture content at time (t), (M_0) is the initial moisture content, (M_e) is the equilibrium moisture content, and Δt is the drying time interval. The equilibrium moisture content was taken as the moisture content obtained at constant weight for each drying temperature.

$$\text{MC (wet basis)}(\%) = \frac{w_t - w_d}{w_t} \times 100\% \quad (1)$$

$$M_t (\text{wb}) = \frac{w_t - w_{db}}{w_d} \quad (2)$$

$$\text{MR} = \frac{M_t - M_e}{M_0 - M_e} \quad (3)$$

$$\text{DR} = \frac{(M_t - M_{t+\Delta t})}{\Delta t} \quad (4)$$

Table 1 presents the seven thin-layer drying models used in this study. These models were selected because they represent common empirical and semi-empirical equations for describing moisture ratio changes during food drying. The selected models include exponential, logarithmic, polynomial, and simplified kinetic forms. This combination allowed the study to compare simple and flexible mathematical structures without adding excessive model parameters. More complex models such as Page and Midilli were not used because the study focused on a defined set of seven models with lower parameter complexity and direct applicability to the available hourly drying data. Nonlinear regression was performed using Microsoft Excel Solver 2016 to estimate the model constants. Model performance was evaluated using the coefficient of determination (R^2), sum of squared errors (SSE), root mean square error (RMSE), and residual analysis. The best model showed the highest R^2 and the lowest SSE and RMSE values.

2.4. Effective Moisture Diffusivity Coefficient (Deff)

In most food materials, drying occurs mainly in the falling-rate period. During this period, internal moisture diffusion controls water movement. Fick's second law can describe this mechanism, as shown in equation (5) [25]. For slab-shaped samples, the analytical solution can be written as equation (6) when the initial moisture distribution is uniform and the effective diffusivity remains constant. where L_0 represents

half of the slab thickness (m), and D_{eff} denotes the effective moisture diffusivity, expressed in m^2/s , and (t) is drying time (s). For long drying periods, equation (6) can be simplified to the first term of the series, as shown in equation (7) [26].

Table 1. Models and equations for fitting the thin-layer drying data of leeks.

Model name	Model equation	References
First order	$MR = a - ae^{-kt}$	[18]
Second order	$MR = a / (1 + kta)$	[19]
Cubic	$MR = a + bt + ct^2 + dt^3$	[20]
Wang and Singh	$MR = 1 + at + bt^2$	[21]
Henderson and Pabis	$MR = ae^{-kt}$	[22]
Vega Lemus	$MR = (a + bt)^2$	[22], [23]
Logarithmic	$MR = ae^{-kt} + b$	[24]

$$\frac{\partial M}{\partial t} = \nabla [D_{\text{eff}} (\nabla M)] \quad (5)$$

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left(- \frac{(2n+1)^2 \pi^2 D_{\text{eff}} t}{4L_0^2} \right) \quad (6)$$

$$MR = \frac{8}{\pi^2} \exp \left(- \frac{\pi^2 D_{\text{eff}} t}{4L_0^2} \right) \quad (7)$$

The logarithmic transformation of equation (7) gives equation (8). The experimental drying data showed a linear relationship between ($\ln MR$) and drying time. The slope of this relationship was used to calculate D_{eff} , as shown in equation (9). This calculation assumed negligible shrinkage during drying. However, leek tissue may shrink as moisture decreases. Therefore, the calculated D_{eff} should be interpreted as an apparent effective moisture diffusivity under the experimental conditions rather than an intrinsic diffusion coefficient.

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{\text{eff}} t}{4L_0^2} \quad (8)$$

$$\text{Slope} = \frac{\pi^2 D_{\text{eff}}}{4L_0^2} \quad (9)$$

$$D_{\text{eff}} = \frac{4L_0^2 \text{slope}}{\pi^2} \quad (10)$$

2.5. Activation Energy (Ea)

To quantify the temperature dependence of the D_{eff} , the Arrhenius model was applied, as described in equation (11) [27], where (D_0) is the pre-exponential factor (m^2/s), E_a is the activation energy (kJ/mol), (R) is the universal gas constant ($0.008314 \text{ kJ mol}^{-1} \text{ K}^{-1}$), and (T) is the absolute temperature (K). Equation (11) was rearranged into its linear form, as shown in equation (12) [28]. The E_a was calculated from the slope of the linear relationship between $\ln D_{\text{eff}}$ and $1/T$, as described by the Arrhenius equation (13).

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (11)$$

$$\ln D_{\text{eff}} = \ln D_0 - \frac{E_a}{RT} \quad (12)$$

$$\text{Slope} = \frac{E_a}{R^2} \quad (13)$$

2.6. Data Analysis

This study used regression analysis and descriptive statistics to evaluate the drying data. Minitab 16 (Minitab Inc., State College, PA, USA) was used for statistical processing, while Microsoft Excel Solver 2016 was used to estimate the model constants. The results from triplicate measurements are presented as mean values and standard deviations where applicable. Model performance was evaluated using the coefficient of determination (R^2), sum of squared errors (SSE), root mean square error (RMSE), and residual analysis.

3. RESULTS AND DISCUSSION

3.1. Leeks Drying Characteristics

Figure 1 presents the drying characteristics of leek leaves during hot-air oven drying at 45, 55, and 65 °C. Drying temperature strongly affected the rate of moisture removal. The moisture ratio decreased continuously at all drying temperatures, and the samples reached equilibrium moisture content faster at higher temperatures. Drying at 65 °C required approximately 240 minutes, whereas drying at 45 °C required nearly 420 minutes. This result shows that moisture removal from leek leaves was highly temperature-dependent.

The higher drying temperature increased heat transfer to the sample surface and strengthened the vapor pressure gradient between the leek tissue and the surrounding air. This condition promoted faster water evaporation from the surface and increased moisture migration from the inner tissue to the surface. Similar behavior was reported for glutinous rice, where drying time decreased progressively when the hot-air temperature increased from 50 to 70 °C [29]. Higher temperatures can shorten drying time, but they may also increase the risk of uneven moisture removal and structural damage [30], [31].

The drying curves showed no constant-rate period. This pattern confirms that the drying process occurred mainly in the falling-rate period. After surface moisture evaporated, water removal depended on the movement of internal moisture through cell walls, vascular tissues, and intercellular spaces. The green leaf portion of leek has fibrous tissue, epidermal layers, and cuticular structures that can restrict internal water movement during drying. As drying continued, cell shrinkage and partial collapse of intercellular pathways likely increased internal resistance to moisture diffusion. Therefore, internal diffusion controlled the drying process rather than surface evaporation alone. This finding agrees with previous studies on leafy vegetables, including bushbuck leaves and Malabar spinach, where the falling-rate period dominated the drying process [28], [31].

The drying rate profile also supports the diffusion-controlled drying mechanism. The drying rate increased rapidly during the early stage of heating and reached the highest value at 65 °C. It then decreased as the moisture ratio approached equilibrium. This decline occurred because the amount of easily removable water decreased and the remaining moisture became more strongly bound within the tissue matrix. Comparable drying-rate patterns were reported for green microalgae and pineapple slices, where higher air temperatures increased the initial evaporation rate but shortened the total drying period [24]. Kumar et al. (2023) [17] also reported that structural shrinkage and chlorophyll degradation may become apparent at temperatures above 55 °C. This suggests that elevated thermal stress can alter surface morphology and affect internal moisture transport. Overall, the drying behavior of leek leaves depended on both drying

temperature and tissue structure. Compared with yam slices and bushbuck leaves, leek leaves showed a relatively slower moisture removal pattern, probably due to their fibrous structure and resistance to internal diffusion [28], [32].

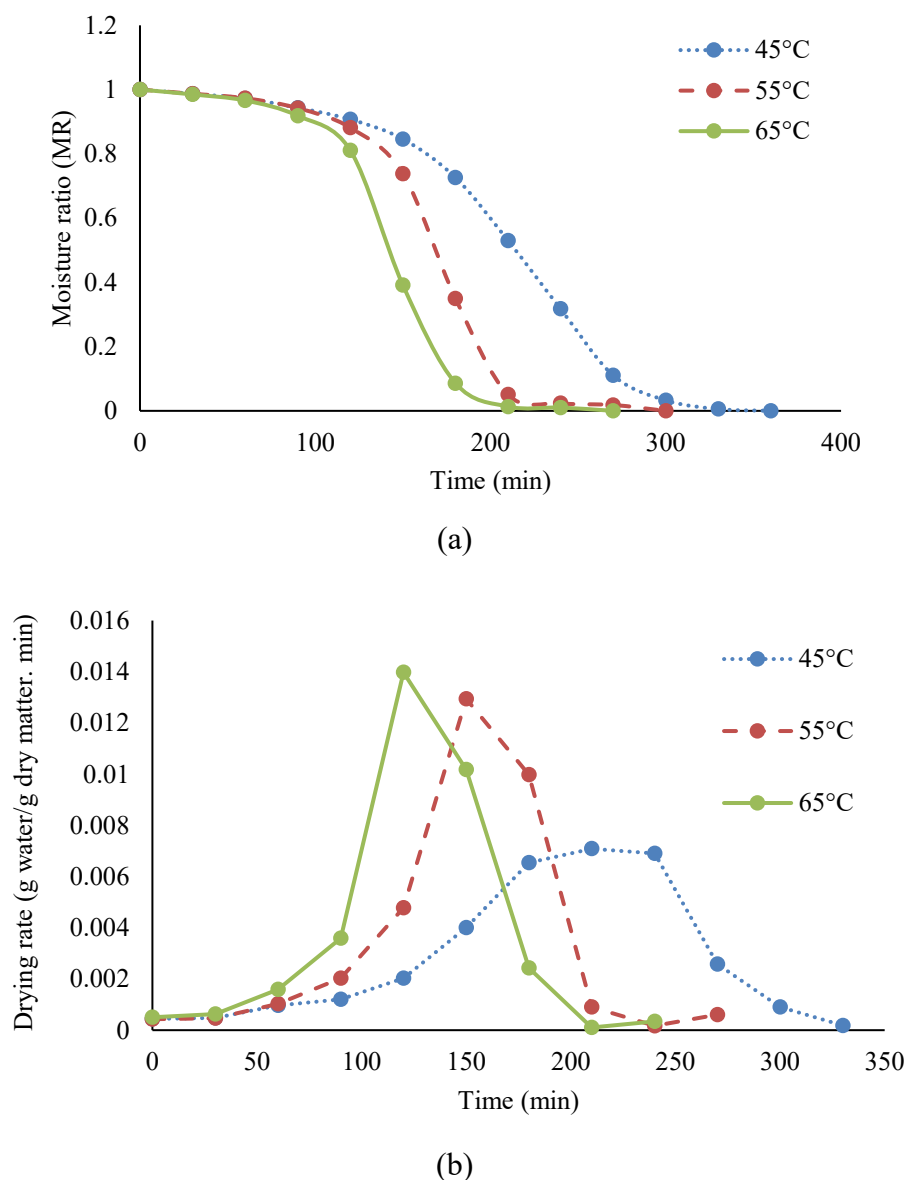


Figure 1. Drying characteristics of leek leaves during hot-air oven drying at different temperatures: (a) moisture ratio versus drying time and (b) drying rate versus drying time.

3.2. Modeling The Drying Kinetics of the HOD

The experimental moisture ratio data were fitted to seven thin-layer drying models to describe the drying behavior of leek leaves at 45, 55, and 65 °C. The models were First-order, Second-order, Cubic, Wang and Singh, Henderson and Pabis, Vega Lemus, and Logarithmic. Table 2 presents the statistical indicators used to evaluate model performance, including R^2 , SSE, and RMSE. The best-fitting model was selected based on the highest R^2 and the lowest SSE and RMSE values.

The Cubic model gave the best fit at 45 °C, with an R^2 of 98.96%, SSE of 0.0593, and RMSE of 0.053. The Wang and Singh model gave the best fit at 55 °C and 65 °C. At 55 °C, this model produced an

R^2 of 92.26%, SSE of 0.0874, and RMSE of 0.078. At 65 °C, it produced an R^2 of 93.17%, SSE of 0.1140, and RMSE of 0.102. These results show that the most suitable model changed with drying temperature. Therefore, one model cannot be assumed to describe leek drying equally well under all thermal conditions.

Table 2. Statistical performance of seven thin-layer drying models for leek leaves at 45, 55, and 65 °C.

Model	Temperature (°C)	R^2	SSE	RMSE	k	Model constant
First-order	45	74.59%	0.2293	0.205	0.0042	–
	55	77.52%	0.1601	0.143	0.0042	–
	65	72.38%	0.2340	0.209	0.0065	–
Second-order	45	64.79%	0.2746	0.246	0.0050	–
	55	68.41%	0.1752	0.157	0.0050	–
	65	62.13%	0.2790	0.250	0.0080	–
Henderson and Pabis	45	84.37%	0.2293	0.205	0.0040	a = 1.2
	55	77.52%	0.1601	0.143	0.0042	a = 1.2
	65	72.38%	0.2340	0.209	0.0060	a = 1.10
Logarithmic	45	92.92%	0.1544	0.138	0.00003	a = 103.28; b = -102.08
	55	86.51%	0.1314	0.118	0.0001	a = 25.372; b = -24.176
	65	86.52%	0.1598	0.143	0.00003	a = 164.7; b = -163.5
Cubic	45	98.96%	0.0593	0.053	–	a = 0.0009; b = -0.027; c = 0.132; d = 0.849
	55	51.29%	2.3068	2.063	–	a = 0.000004; b = -0.002; c = 0.14; d = 0.853
	65	49.83%	1.9453	1.740	–	a = 0.000005; b = -0.002; c = 0.14; d = 0.853
Wang and Singh	45	98.61%	0.0683	0.061	–	a = 0.03; b = -0.01
	55	92.26%	0.0874	0.078	–	a = 0.0002; b = -0.00002
	65	93.17%	0.1140	0.102	–	a = 0.0004; b = -0.00002
Vega Lemus	45	88.50%	0.1967	0.176	–	a = -1.16; b = 0.06
	55	79.58%	0.1483	0.133	–	a = -1.104; b = 0.0025
	65	79.09%	0.1288	0.115	–	a = -1.1; b = 0.003

The Cubic model described the drying curve well at 45 °C, where moisture removal occurred more gradually. Its equation, $MR = at^3 + bt^2 + ct + d$, produced coefficients of a = 0.0009, b = -0.027, c = 0.132, and d = 0.849. However, the Cubic model performed poorly at 55 and 65 °C, with R^2 values of 51.29% and 49.83%, respectively. These low values indicate that the model could not adequately represent the sharper decline in moisture ratio at higher temperatures. For this reason, the Cubic model should only be considered suitable for the 45 °C drying condition in this study.

At higher temperatures, the Wang and Singh model gave better predictions. This model uses the equation $MR = 1 + at + bt^2$, which can capture the curved decline in moisture ratio during rapid drying. The estimated constants were a = 0.0002 and b = -0.00002 at 55 °C, and a = 0.0004 and b = -0.00002 at 65 °C. The higher value of (a) at 65 °C reflects faster moisture reduction under a stronger temperature gradient. The negative (b) value shows the progressive decrease in drying rate as internal moisture became less available. This behavior agrees with the falling-rate drying pattern observed in section 3.1.

The better performance of the Wang and Singh model at 55 and 65 °C may relate to the faster transition from surface evaporation to internal diffusion at higher temperatures. Under these conditions, the moisture ratio decreased more sharply during the middle stage of drying. The second-order structure of the Wang and Singh model represented this curvature more effectively than the Cubic, First-order, Second-

order, Henderson and Pabis, Vega Lemus, and Logarithmic models. Similar findings were reported for *Centella asiatica* leaves, where the Wang and Singh model gave a higher fitting accuracy than the Logarithmic model at 50 °C [33]. Comparable results were also reported for *Tremella fuciformis* [20], where polynomial and semi-empirical models described drying behavior well at elevated temperatures.

3.3. Determination of Effective Moisture Diffusivity (Deff)

Figure 2 shows that the effective moisture diffusivity (Deff) values of leeks increased with temperature. The Deff value increased from $9.13 \times 10^{-9} \text{ m}^2/\text{s}$ at 45 °C to $31.69 \times 10^{-9} \text{ m}^2/\text{s}$ at 55 °C, and further to $43.36 \times 10^{-9} \text{ m}^2/\text{s}$ at 65 °C. This trend indicates that higher drying temperatures increased the internal movement of water in leek tissue. Greater thermal energy reduced water viscosity and strengthened the vapour pressure gradient between the inner tissue and the sample surface. As a result, moisture moved more rapidly through cell pores, vascular tissues, and intercellular spaces.

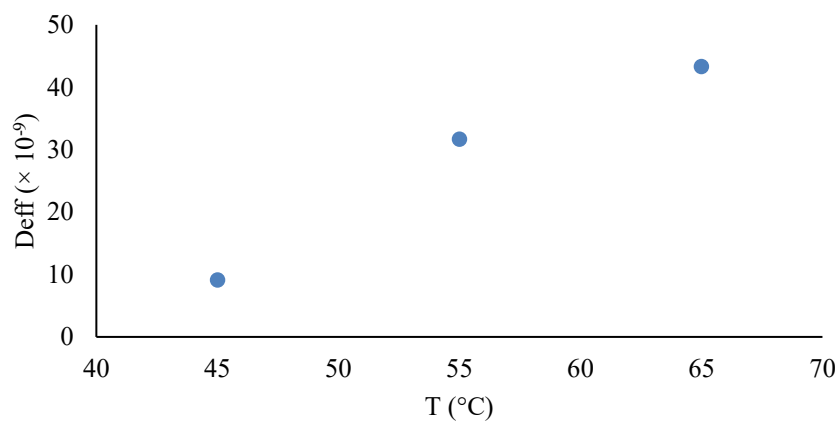


Figure 2. Effective moisture diffusivity of leek leaves at different hot-air oven drying temperatures.

The obtained Deff values were higher than those reported in previous leek drying studies. Doymaz and Özdemir [34] reported lower diffusivity values for cabinet-dried leek slices. Several factors may explain this difference. First, this study used the green leaf portion, which has wider exposed surfaces after cutting and may allow faster water migration than thicker pseudo-stem tissues. Second, sample geometry and thickness influence the calculated diffusion path length. A shorter or more open moisture pathway can increase the apparent Deff. Third, the drying temperature range used in this study, especially 55 and 65 °C, may have increased internal vapor movement more strongly than the conditions used in previous leek studies [35]. Tissue shrinkage may also affect the estimation because the Fickian model assumes constant geometry during drying [36].

These findings show that Deff should be interpreted as an apparent effective diffusivity under the present drying conditions. The higher values suggest that hot-air oven drying can accelerate moisture removal [37]. However, industrial-scale drying should control temperature, sample thickness, loading density, airflow, and humidity to avoid uneven drying and quality loss. Therefore, the calculated Deff values provide useful baseline data for designing and scaling up leek leaf drying processes.

3.4. Determination of Activation Energy (Ea)

Figure 3 presents the Arrhenius relationship between $\ln \text{Deff}$ and the reciprocal absolute temperature ($1/T$). The regression equation was $\ln \text{Deff} = -8429.7(1/T) + 8.13$, with an R^2 value of 0.9042. Based on this slope, this study calculated an activation energy E_a of 70.08 kJ/mol for moisture diffusion in leek leaves. The E_a value indicates the energy required to initiate moisture movement within the leek tissue. This value falls within the general range reported for agricultural materials, which is 12–110 kJ/mol [33]. However, it is higher than the values reported for lily scales and yam slices, which reached 42.42 and 40.31

kJ/mol, respectively [32], [38]. The higher E_a suggests that leek leaves require greater energy for internal water migration [39], [40]. The fibrous structure, cuticular layer, and compact tissue arrangement of leek leaves may increase resistance to moisture movement during drying [41].

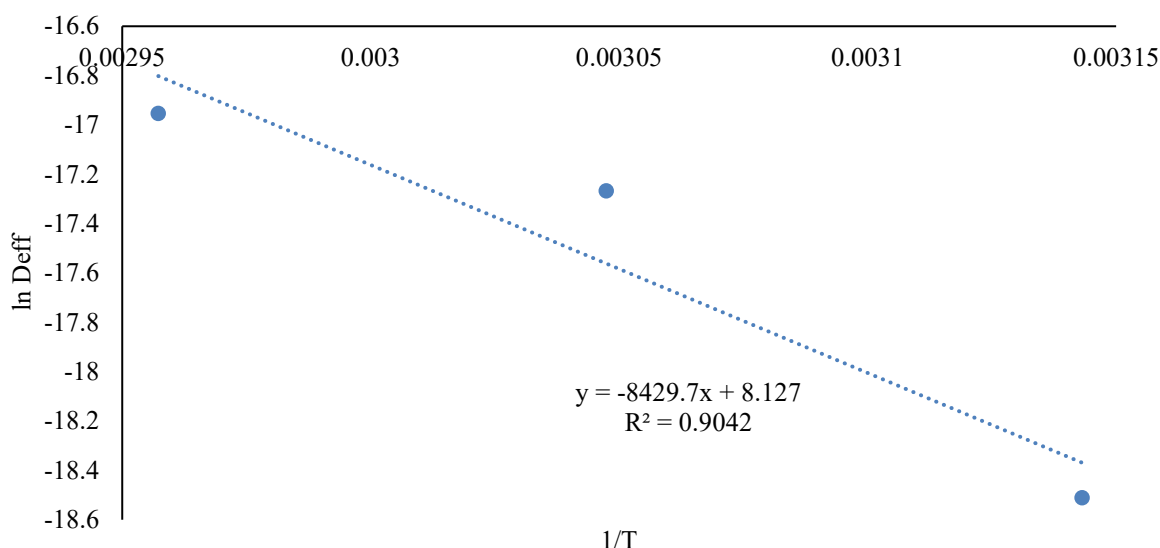


Figure 3. Arrhenius relationship between $\ln Deff$ and reciprocal absolute temperature ($1/T$) for leek leaves.

The result also shows that drying temperature strongly affected moisture diffusion. Higher temperatures provided enough thermal energy to overcome internal resistance and increase $Deff$. This explains why the samples dried faster at 55 and 65 °C than at 45 °C. However, this study estimated the Arrhenius relationship using only three drying temperatures. This limited number of data points reduces the robustness of the regression. Future work should include more temperature levels to improve the reliability of E_a estimation and to better define the temperature dependence of moisture diffusion in leek leaves.

4. CONCLUSION

This study characterised the drying kinetics, effective moisture diffusivity, and activation energy of leek leaves (*Allium ampeloprasum* var. porrum) during hot-air oven drying. The drying process occurred in the falling-rate period, which indicates that internal diffusion controlled water movement in the leaf tissue. Higher drying temperatures shortened drying time and increased effective moisture diffusivity. Among the seven evaluated models, the Cubic model best described drying at 45 °C, while the Wang and Singh model gave the best fit at 55 and 65 °C. These results show that model performance depends on drying temperature and tissue response. The main contribution of this study lies in providing part-specific kinetic data for the green leaf portion of leek, which has different structural characteristics from the white pseudo-stem. The findings provide useful parameters for designing practical hot-air drying conditions for leek leaves and similar leafy vegetables. Future studies should evaluate airflow, humidity, shrinkage, colour, nutrient retention, and texture to support industrial-scale drying optimisation.

AUTHOR CONTRIBUTION

Satria Bhirawa Anoraga: Writing (original draft), writing (review & editing), formal analysis, supervision, conceptualization. **Nadia Awalina Bunga Massita:** Writing (review & editing), investigation, funding acquisition, supervision. **Chyntia Diva Omega:** investigation, formal analysis. **Octhateani**

Adiibah Wigati: investigation, formal analysis. **Sang Norma Lintang Asmara:** Writing (review & editing), supervision. **Jhauharotul Muchlisyyahb:** supervision, conceptualization. **Jamilu Suleiman:** Writing (review & editing), supervision.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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