

Influence of Temperature and Ginger Piece Size on Heat and Mass Transfers During Convective Drying

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Received May 13, 2025; Revised June 15, 2025; Accepted June 23, 2025

Abstract This study examines the influence of temperature and sample size on the drying of ginger in a convective dryer. Cubic samples of various sizes (0.5 cm, 1 cm, 1.5 cm, and 2 cm) were dried at temperatures of 50°C, 60°C, 70°C, and 80°C. The results show that increasing the temperature accelerates the drying process and reduces the time required to reach an almost negligible level of residual moisture. Furthermore, smaller samples dry faster than larger ones due to their reduced thickness and improved water diffusion. These findings highlight the importance of controlling both sample size and temperature to optimize the drying process while preserving the quality of the ginger. The diffusion coefficient values calculated for cubic samples with different sizes of 0.5 cm, 1 cm, 1.5 cm, and 2 cm at temperatures of 50°C, 60°C, 70°C, and 80°C range from 3.019×10^{-10} to 7.109×10^{-9} m²/s, and they increase with air temperature. The activation energy calculated using the Arrhenius equation ranges from 16.72 to 60.75 kJ/mol, and it increases with sample size.

Keywords: Convective drying, ginger, temperature, drying rate, residual moisture, diffusion coefficient, size

Cite This Article: SAWADOGO Ladifou, OUOBA Kondia Honoré, GANAME Abdou-Salam, IBRANGO Abdoul Salam, and BAMA Désiré, "Influence of Temperature and Ginger Piece Size on Heat and Mass Transfers During Convective Drying." *Journal of Materials Physics and Chemistry*, vol. 13, no. 1 (2025): 1-7. doi: 10.12691/jmpc-13-1-1.

1. Introduction

Drying is one of the oldest techniques used to preserve agricultural food products. This process, which relies on heat and mass transfer to remove water, is an effective means to limit post-harvest losses and extend the shelf life of products beyond the production season. Moreover, it facilitates the transport of goods to urban centers [1].

Although widely used in the food industry, drying is traditionally practiced by many African farmers [2]. This process, which stabilizes products by lowering their water activity, must nevertheless meet specific quality criteria [3]. Convective drying, in particular, plays a key role in the transformation and preservation of food products by reducing their moisture content to ensure optimal microbiological and chemical stability [1]. This technique is commonly employed in the processing of spices, fruits, vegetables, and roots, such as ginger, which is an essential resource for both the food and pharmaceutical industries.

Ginger, renowned for its aromatic and medicinal properties, is particularly sensitive to moisture. Inadequate

drying management can lead to significant quality losses, such as the deterioration of its bioactive compounds such as gingerols and shogaols. Also its texture, and its color are affected [4]. Consequently, a comprehensive understanding of the mass transfer mechanisms during the convective drying of ginger is crucial for optimizing the process and preserving its qualities.

During convective drying, parameters such as temperature, air velocity, and particle size influence moisture transfer [5]. In particular, sample size plays a crucial role: it determines the contact surface and the internal diffusion distance, which directly impacts the drying kinetics. However, the precise effects of particle size on these transfers remain poorly documented, especially for tropical products like ginger. Although many studies have addressed the drying of food products such as potatoes, sweet potatoes, or rice, there is still little research dedicated to tropical products like ginger [6].

Thus, essential questions remain: How does the size of ginger samples affect the drying rate, and which mechanisms predominate in moisture transfer based on sample size? Accurately predicting the drying kinetics of agricultural products is indispensable for determining the optimal operating conditions.

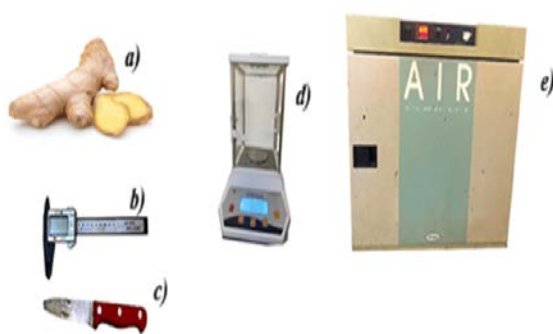
2. Materials and Methods

2.1. Materials and Experimental Protocol

As we can see in figure 1, the following materials are used: an electronic scale, a caliper, an oven, and a stainless steel knife. **Measurement tools:** An electronic caliper was used to monitor the thickness reduction due to shrinkage. **Drying equipment:** An oven is a device used to remove moisture from materials with a heated airflow. An electronic scale is used to obtain precise weight measurements. **Software:** Excel was used for calculations and graphs.

For For this study, fresh, high-quality ginger was used. This ginger, scientifically named *Zingiber officinale*, is the root of a perennial plant from the Zingiberaceae family. The ginger used in our work was purchased at the market in Sector 22 of Bobo-Dioulasso, the economic capital of Burkina Faso. It was then transported to the Laboratory of Materials, Heliophysics, and Environment (La.M.H.E) at the University Nazi Boni.

The ginger rhizomes were washed before being peeled. The ginger was then peeled and cut into five types of cubic samples with edge lengths of approximately 0.5 cm, 1 cm, 1.5 cm, 1.7 cm, and 2 cm. Each type of sample was prepared in three (3) replicates to verify the consistency of the results. The cutting process was performed on a table using a well-sharpened stainless steel knife, and the dimensions of the samples were precisely measured with a ruler. Before being placed in an oven (AIR Concept, with a temperature range of 40°C to 250°C and a digital display) the initial mass of each sample was recorded using an electronic scale (SARTORIUS, 0.001 g precision). Since the samples were grouped into sets of three with similar dimensions, a permanent ink marker was used for differentiation.



a) Fresh ginger samples;
b) Vernier caliper for dimensional measurements;
c) Stainless steel knife for sample preparation;
d) High-precision electronic balance for mass determination;
e) Laboratory drying oven for controlled dehydration.

Figure 1. Equipment used during the experiment

The ginger cubes were weighed and evenly distributed on an oven tray. Drying was carried out at temperatures of 50°C, 60°C, 70°C, and 80°C, with constant airflow to ensure uniform evaporation of moisture. Samples were taken every 10 minutes to measure their mass. After each drying test, the samples were further dried at 100°C for at

least 24 hours to obtain their dry mass and determine their initial moisture content. The water content was determined according to AOAC (1980) methods.

The drying rate of the ginger cubes was calculated based on the mass of water removed per unit of time and per kilogram of dry matter (solid), expressed in units of kg/kg.s. This methodology enables a precise assessment of the drying dynamics of ginger and provides reliable data for validating the developed mathematical model. Finally, Excel software was used for calculations and graph construction.

2.2. Data Processing

2.2.1. Drying Kinetics

➤ Moisture Content

The moisture content X is expressed in kilograms of water per kilogram of dry matter (kg w /kg dm). It evolves over time depending on the drying conditions. The mathematical relationship is given by:

$$X(t) = \frac{m_{\text{water}}}{m_{\text{dry matter}}} \quad (1)$$

m_{water} represents the mass of water contained in ginger, and $m_{\text{dry matter}}$ corresponds to the mass of dry matter in ginger.

2.2.2. Drying Rate

The rate of water removal is high and depends on the drying conditions (temperature, air flow rate). The drying rate ($-dX/dt$) is a direct measure of moisture transfer per unit of time. It is obtained by the time derivative of the moisture content: ($-dX/dt$) It represents the rate of moisture loss.

2.2.3. Estimation of the Diffusion Coefficient and Activation Energy

To estimate the moisture diffusion coefficient in ginger samples shaped as cubes, Fick second law of diffusion is applied, with adaptations to suit the cubic geometry. Since moisture movement within a cube involves three-dimensional diffusion, exact analytical solutions are rarely found in existing literature. However, to facilitate the estimation of the effective diffusion coefficient, it is common to adopt simplified geometric models for instance, by approximating the sample as an infinite slab or using an equivalent sphere.

➤ One-Dimensional Slab Approximation

When moisture diffusion predominantly occurs in a single direction, the cubic sample can be treated as a flat slab with a half-thickness $L = a/2$. This simplification allows the use of classical one-dimensional diffusion equations [7]:

$$MR = \frac{X_t - X_{eq}}{X_0 - X_{eq}} = \text{erf}\left(\frac{L}{2\sqrt{D_{eff}t}}\right) \quad (2)$$

This method, although simple and efficient for modelling one-dimensional diffusion, may not adequately

capture the full complexity of moisture transfer in a cubic ginger sample, where diffusion occurs in all three spatial directions.

► Equivalent Sphere Approach (3D)

In this approach, the cubic sample is approximated as a sphere with an equivalent radius defined as $R = L/2$, where L is the half-length of the cube. This simplification enables the use of the classical analytical solution of Ficks law for spherical geometry, which is typically expressed as a series expansion [8].

$$MR = \frac{X_t - X_{eq}}{X_0 - X_{eq}} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n^2 \frac{\pi^2 D_{eff} t}{R^2}\right) \quad (3)$$

Where R is the equivalent radius of the sphere, D_{eff} is the effective diffusion coefficient, and n is a positive integer.

Although this method provides a closer approximation to three-dimensional behavior than the flat-plate model, it still has limitations, as a cube does not exhibit the exact same moisture transfer characteristics as a sphere.

► Infinite Slab (3D Cube) Approach

This approach relies on the exact analytical solution of Fick's second law for a cubic geometry, typically expressed as a series expansion adapted to three-dimensional diffusion conditions [7].

$$MR = \frac{X_t - X_{eq}}{X_0 - X_{eq}} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-(2n+1)^2 \cdot \frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (4)$$

L represents the sample length, D_{eff} is the effective moisture diffusivity, and n is a positive integer.

Infinite Slab Approach:

This method produced diffusion coefficient values that were not consistent with those reported in the literature, highlighting its limitations when applied to cubic geometries. A widely used strategy for modeling ginger drying is to approximate cubic samples as equivalent spheres. This method offers a good trade-off between computational simplicity and accuracy, particularly in cases where a full analytical solution is not practical or available [9].

In our study, the ginger samples were cubic in shape. The diffusion coefficients were estimated using solutions derived from Fick law, adapted to fit the geometry of the samples. Since there is no exact analytical solution for moisture diffusion in a cube, two approximation methods were evaluated based on existing literature.

- Infinite Plate Model: This approximation yielded diffusion coefficients that deviated from literature values, indicating its lack of suitability for this application.

- Equivalent Sphere Model: In this method, the cube is approximated as a sphere with an equivalent radius, $R = a/2$. This approach yielded diffusion values consistent with published data [10].

When considering long drying times ($X_r < 0.6$), Equation (2) can be simplified by retaining only the first term of the series expansion. Applying the natural logarithm to both sides of Equation (2) leads to the following linear expression:

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) + \left(-\frac{\pi^2 D_{eff} t}{R^2}\right) \quad (5)$$

$$\text{For } R = \frac{a}{2} \quad (6)$$

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{\left(\frac{a}{2}\right)^2}\right) = A - kt \quad (7)$$

by identification

$$k = \frac{\pi^2 D_{eff}}{\left(\frac{a}{2}\right)^2} \quad (8)$$

$$D_{eff} = k \left(\frac{a}{2\pi}\right)^2 \quad (9)$$

The activation energy is typically estimated using the Arrhenius equation [11].

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (10)$$

In this context, D_0 represents the pre-exponential factor in the Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), T is the drying temperature (K), and R is the universal gas constant ($\text{kJ/mol}\cdot\text{K}$).

By taking the natural logarithm of both sides of Equation (10), the Arrhenius expression can be linearized into its logarithmic form.

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{R} \cdot \frac{1}{T} = B - k' \frac{1}{T} \quad (11)$$

$$B = \ln(D_0) \quad (12)$$

$$k' = \frac{E_a}{R} \quad (13)$$

3. Results and Discussion

3.1. Drying Kinetics

Figure 2 displays the experimental data illustrating that the moisture ratio (X/X_0), also referred to as the reduced moisture content, decreases exponentially over time for all ginger samples.

At 80°C , the smallest sample size (0.5 cm) reaches a moisture ratio of 1.1% after 120 minutes . At lower drying temperatures of 70°C , 60°C , and 50°C , the same sample size records moisture ratios of 1.5% , 6% , and 7.14% , respectively, at the same drying duration. These values

correspond to reductions in initial moisture content of

approximately 98.9% at 80°C, 98.5% at 70°C, 94% at 60°C, and 92.86% at 50°C.

These results clearly demonstrate that drying temperature significantly affects the drying rate: higher temperatures accelerate moisture evaporation, resulting in a more substantial decline in the moisture ratio (X/X_0). In addition to temperature, sample size also plays a critical role in drying kinetics at a constant temperature:

- At 50°C, the moisture ratio ranges from 7.14% for 0.5 cm slices to 56% for 2 cm samples.
- At 80°C, it ranges from 1.1% to 43% for the same sizes

These findings confirm that smaller samples dry faster due to their larger surface-to-volume ratio, which enhances moisture transfer. Therefore, both drying temperature and sample dimensions significantly influence drying behavior. These trends align with findings from previous studies on the drying of other agricultural products such as carrots and tomatoes [8,12].

3.2. Drying Rate of Ginger

Figure 3 illustrates the drying rate curves as a function of time for ginger samples of various sizes (0.5 cm, 1 cm, 1.5 cm, 1.7 cm, and 2 cm) subjected to different drying temperatures (50°C, 60°C, 70°C, and 80°C).

The curves exhibit an initial increase in drying rate followed by a gradual decrease, representing the two characteristic stages of the drying process: an initial constant-rate period, dominated by surface water

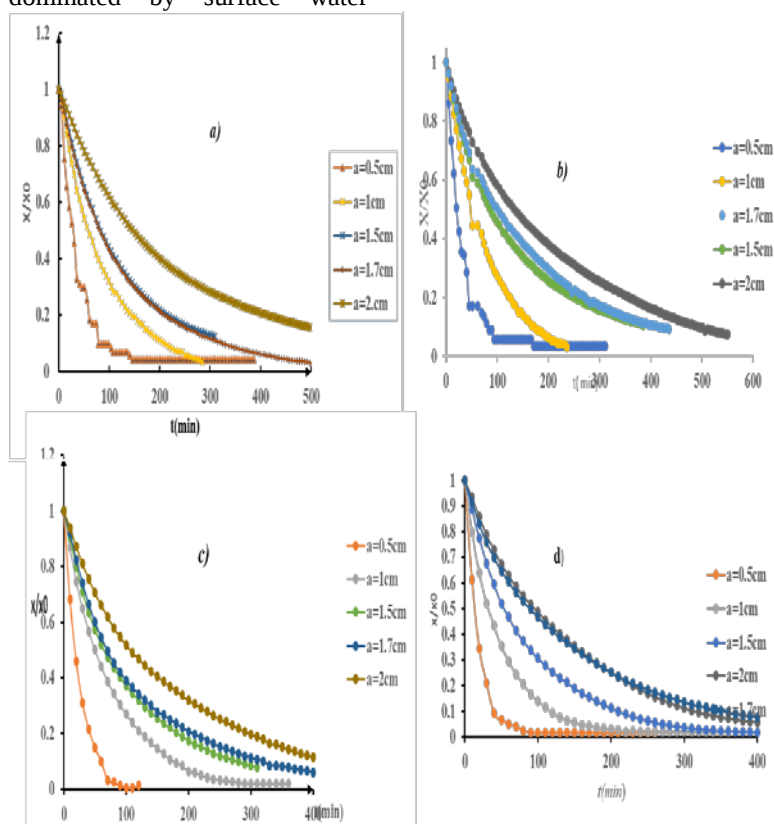
evaporation, and a falling-rate period, during which internal moisture diffusion becomes the controlling mechanism.

For instance, at 70°C, the smallest samples (0.5 cm and 1 cm) reach peak drying rates of approximately 0.68 kg/kg·min early in the process, whereas the 2 cm samples peak at only about 0.24 kg/kg·min. This behavior can be attributed to the smaller samples' higher surface-area-to-volume ratio, which enhances moisture diffusion.

Raising the temperature significantly accelerates the drying kinetics. At 80°C, the initial drying rate for a =0.5 cm sample is around 0.05 kg/kg·min, compared to only 0.015 kg/kg·min at 50°C. This temperature effect is even more pronounced in larger samples: a=2 cm cube exhibits a peak rate of approximately 0.014 kg/kg·min at 50°C, while reaching 0.02 kg/kg·min at 80°C.

These findings highlight that smaller ginger pieces (0.5 to 1 cm) dry more rapidly, making them suitable for industrial applications that require quick moisture removal. Conversely, larger pieces (1.7 to 2 cm) demand either longer drying times or higher temperatures to achieve similar final moisture levels.

The experimental trends align with the results reported by Bai et al. (2023) [4,5], who also demonstrated that particle size has a strong influence on heat and mass transfer during ginger drying. Additionally, the drying behavior observed in this study is consistent with that reported for other agricultural products such as carrots and mint [6,10].



a) Convective drying curves of cubic-shaped ginger samples of different sizes at $T = 50^\circ\text{C}$;
 b) Convective drying curves of cubic-shaped ginger samples of different sizes at $T = 60^\circ\text{C}$;
 c) Convective drying curves of cubic-shaped ginger samples of different sizes at $T = 70^\circ\text{C}$;
 d) Convective drying curves of cubic-shaped ginger samples of different sizes at $T = 80^\circ\text{C}$;

Figure 2. Variation of experimental reduced moisture content of ginger as a function of drying time

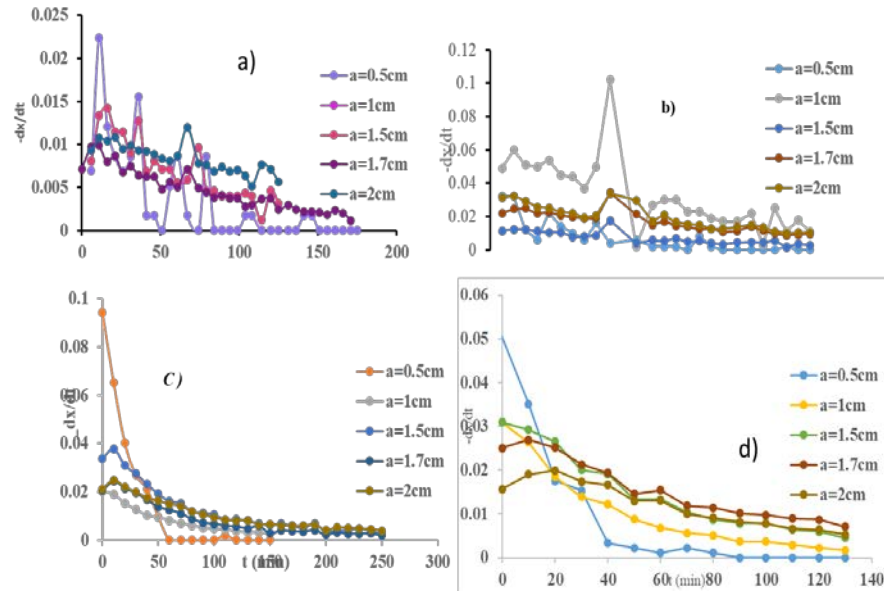


Figure 3. Drying rate curves of ginger samples as a function of drying time under convective drying conditions

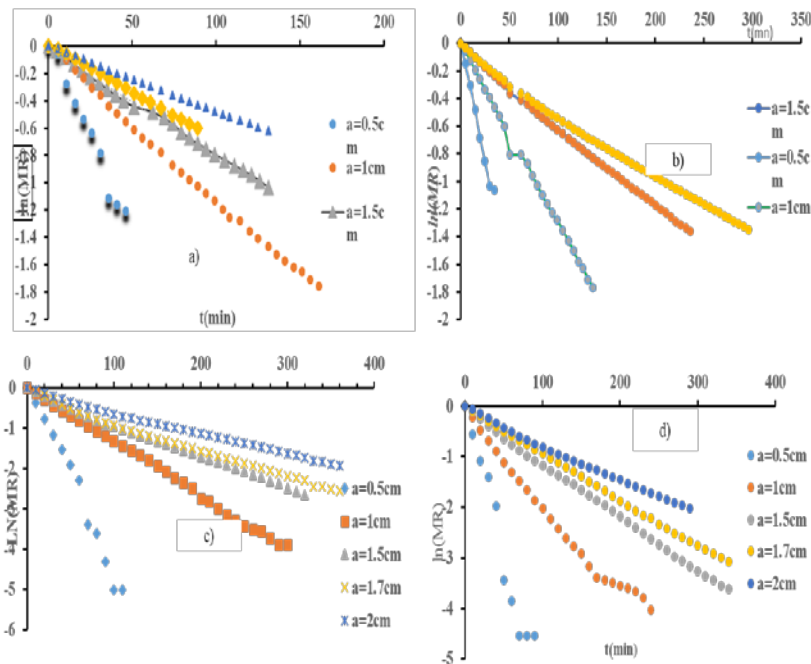


Figure 4. Evolution of $\ln(MR)$ as a function of drying time for cubic ginger samples

Table 1. Effective Diffusion Coefficients (D_{eff}) of Ginger Samples at Different Temperatures and Sizes

Ginger Size	Effective Diffusion Coefficient D_{eff} (m^2/s)			
	$50\text{ }^{\circ}\text{C}$	$60\text{ }^{\circ}\text{C}$	$70\text{ }^{\circ}\text{C}$	$80\text{ }^{\circ}\text{C}$
0.5cm	3.019×10^{-10}	3.45×10^{-10}	5.14×10^{-10}	6.07×10^{-10}
1cm	4.64×10^{-10}	5.45×10^{-10}	5.66×10^{-10}	6.76×10^{-10}
1.5cm	5.89×10^{-10}	6.84×10^{-10}	7.50×10^{-10}	1.01×10^{-9}
1.7cm	6.69×10^{-10}	6.95×10^{-10}	8.30×10^{-10}	1.11×10^{-9}
2cm	8.11×10^{-10}	8.61×10^{-10}	8.78×10^{-10}	7.11×10^{-9}

3.3. Evolution of Effective Diffusivity over Time

Figure 4 illustrates the evolution of $\ln(MR)$ as a function of drying time for cubic ginger samples. This representation highlights the typical exponential trend observed during drying, thereby facilitating the fitting to the mathematical models used.

Equations (7) and (8) were used to populate Table 1, from which the effective diffusion coefficients (D_{eff}) were determined. The smallest samples (0.5 cm and 1 cm) exhibited lower diffusion coefficients compared to the larger ones (1.7 cm and 2 cm). This may be attributed to a more efficient moisture distribution from the surface, which enhances mass transfer.

As drying temperature increased from 50°C to 80°C, a corresponding upward trend in the effective diffusivity was observed (Table 1). Both temperature and sample size had a noticeable impact on the diffusion behavior of ginger during drying. These observations are consistent with previously reported findings in the literature [6], obtained at different drying temperatures (50, 60, 70, and 80°C) and for various cube sizes (0.5; 1; 1.5; 1.7; and 2 cm), ranged from 3.019×10^{-10} to 7.109×10^{-9} m²/s. A general increase in D_{eff} was observed with increasing temperature and sample size (see Tab 1). These findings align with diffusion coefficient ranges reported for other food products, such as $2.641\text{--}5.711 \times 10^{-9}$ m²/s for green beans [15], and 2.15×10^{-8} to 1.71×10^{-7} m²/s for mint [16] and tomato [8].

3.4. Influence of Sample Size on Activation Energy

Table 2. Influence of Sample Size on Activation Energy

size (cm)	0,5	1	1,5	1,7	2
Ea.(kJ/mol)	16,72	17,85	29,59	30	60,75

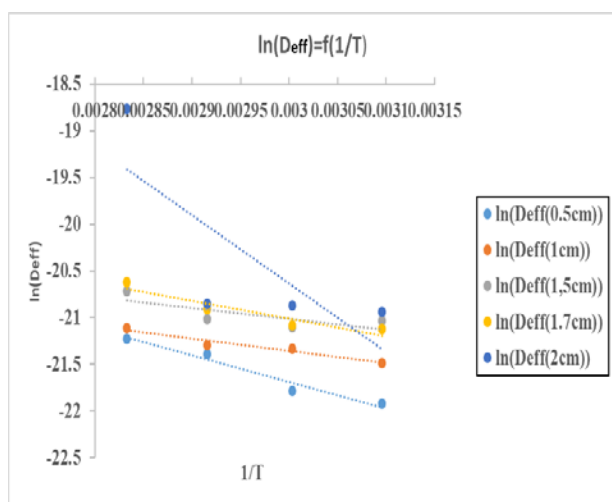


Figure 5. Variation of $\ln(D_{eff})$ as a Function of the Inverse of Temperature ($1/T$)

Activation energy is the minimum energy that must be supplied to a system for a thermally activated process to occur.

The plot of $\ln(D_{eff})$ versus $1/T$ produces straight lines (Figure 5), from which the slopes allow us to determine

the activation energies using Equation (12). These values are presented in Table 2. Based on the data, it is evident that sample size significantly affects the activation energy of ginger. The obtained values fall within the range reported for other agricultural products [9,10], confirming the validity of the results.

4. Conclusion

This study highlights the significant impact of ginger particle size and drying temperature on heat and mass transfer during convective drying. Smaller ginger pieces (ranging from 0.5 cm to 1.5 cm) exhibited faster drying rates due to more efficient moisture diffusion, whereas larger pieces experienced slower drying, primarily limited by internal moisture migration.

The analysis of drying rates and diffusion coefficients confirms that temperature is a key factor in optimizing the drying process. Higher temperatures enhance moisture removal but must be carefully regulated to prevent the degradation of ginger's bioactive compounds.

The results emphasize the importance of tightly controlling drying conditions to improve energy efficiency and maintain the quality of the final product. For optimal drying performance, particle sizes between 0.5 cm and 1.5 cm are recommended, along with precise management of drying temperatures. Future research could focus on numerical modeling of heat and mass transfer to gain deeper insights and further improve industrial drying applications.

Declaration of competing Interests

The authors affirm that there are no conflicts of interest associated with this publication.

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