DOI: 10.29244/jmpi.2025.12.2.141

Jurnal Mutu Pangan Vol. 12(2): 141-150, 2025
ISSN 2355-5017

Effect of Drying Temperature and Slice Thickness on Drying Kinetics, Moisture Diffusivity, Energy Use, and Color Change in Convectively Dried Chayote Squash Slices

Pengaruh Suhu Pengeringan dan Ketebalan Irisan terhadap Kinetika Pengeringan, Difusivitas Kelembapan, Penggunaan Energi, dan Perubahan Warna pada Irisan Labu Siam yang Dikeringkan Secara Konvektif

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Abstract. Insufficient fiber intake is strongly associated with chronic diseases. Chayote squash (*Sechium edule*), widely available in Indonesia, has potential as a fiber source, and drying provides a practical method for its use in food products. This study evaluated the drying kinetics, specific energy consumption (SEC), total color change (ΔE^*_{ab}), and effective moisture diffusivity (D_{eff}) of chayote slices under different temperatures (50, 60, and 70 °C) and thicknesses (3 and 6 mm) to determine the optimum drying conditions. Drying time (DT) ranged from 150 min (70 °C, 3 mm) to 350 min (50 °C, 6 mm). The approximation of diffusion and the Midilli and others models best represented the drying kinetics. The highest SEC was 3.40×10^6 kJ·kg⁻¹ (60 °C, 3 mm), while other treatments showed no significant differences. D_{eff} increased with temperature and thickness (3.38×10^{-10} to 1.28×10^{-9} m²·s⁻¹). Food color, an important factor influencing consumer acceptance, showed no significant ΔE^*_{ab} differences across treatments. The optimum drying condition determined was 70 °C with 3 mm slices (DT of 149 min, ΔE^*_{ab} of 16.62, SEC of 3.02×10^6 kJ·kg⁻¹). These findings provide insights into designing chayote drying processes that achieve desirable quality while minimizing energy consumption.

Keywords: chayote squash, model fitting, optimization, temperature, thickness

Abstrak. *Asupan serat yang tidak mencukupi sangat terkait dengan penyakit kronis. Labu siam (Sechium edule), yang banyak tersedia di Indonesia, berpotensi sebagai sumber serat, dan pengeringan merupakan metode praktis untuk pemanfaatannya dalam produk pangan. Penelitian ini mengevaluasi kinetika pengeringan, konsumsi energi spesifik (Specific Energy Consumption/SEC), perubahan warna total (ΔE^*_{ab}), dan difusivitas kelembapan efektif (D_{eff}) pada irisan labu siam dengan variasi suhu (50, 60, dan 70 °C) serta ketebalan (3 dan 6 mm) untuk menentukan kondisi pengeringan optimum. Waktu pengeringan (Drying Time/DT) berkisar antara 150 menit (70 °C, 3 mm) hingga 350 menit (50 °C, 6 mm). Model approximation of diffusion dan Midilli and others paling sesuai dalam merepresentasikan kinetika pengeringan. Nilai SEC tertinggi adalah $3,40\times10^6$ kJ.kg^{-1} (60 °C, 3 mm), sedangkan perlakuan lain tidak menunjukkan perbedaan signifikan. Nilai D_{eff} meningkat seiring kenaikan suhu dan ketebalan ($3,38\times10^{-10}$ hingga $1,28\times10^{-9}$ m^2.s^{-1}). Warna pangan, sebagai faktor penting yang memengaruhi penerimaan konsumen, tidak menunjukkan perbedaan ΔE^*_{ab} yang signifikan antar perlakuan. Kondisi pengeringan optimum ditentukan pada suhu 70 °C dengan ketebalan irisan 3 mm (DT 149 menit, ΔE^*_{ab} 16,62, SEC $3,02\times10^6$ kJ.kg^{-1}). Hasil ini memberikan masukan dalam merancang proses pengeringan labu siam untuk mencapai mutu yang diinginkan dengan konsumsi energi yang minimal.*

Kata kunci: *labu siam, pemodelan, optimasi, suhu, ketebalan*

Practical Application: The results of this study can be utilized in designing drying processes that achieve chayote slices with optimum quality characteristics (such as color) while minimizing energy usage. Moreover, the information on moisture diffusivity and drying kinetics of the dried chayote slices can provide insights into factors that affect the drying process and the interaction among these factors.

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DOI: 10.29244/jmpi.2025.12.2.141

INTRODUCTION

Chronic non-communicable diseases represent the leading cause of illness worldwide, and poor dietary habits, such as insufficient intake of fruits, grains, and fiber, are key contributing factors (Zhuo *et al.* 2023). In Indonesia, fiber consumption remains far below recommended levels, averaging only 10.5 g per day compared to the recommended 34 g per day (Djojosaputro and Prihantini 2023). This deficiency has been linked to cardiovascular disease, which is the country's primary cause of morbidity and mortality (Directorate of Prevention and Control of Non-Communicable Diseases 2017; Gunawan *et al.* 2021).

To address this gap, chayote squash (*Sechium edule*), a vegetable containing about 0.49 g_w g_{ds}^{-1} (dry basis) of dietary fiber (Salam *et al.* 2023) shows potential as an alternative fiber source. It is found in abundance in many parts of the world, including Indonesia. This country produced 0.44 million tons of chayote squash in 2024, comparable to the production of cucumbers at 0.4 million tons in the same year (BPS-Statistics Indonesia 2025). Hence, this commodity has the potential to be developed as a functional food ingredient or a fiber source. Moreover, due to its bland taste (Sangma *et al.* 2019), chayote can be integrated into various industrial applications, especially in dried form. Further, dried chayote slices can be transformed into powder, and the powdered form of chayote squash can serve as a natural, fiber-rich ingredient in creating enhanced-value functional foods (Minarovičová *et al.* 2018). Therefore, drying is a valuable method for incorporating it into various products, and developing dried chayote squash (*Sechium edule*) is essential.

Convective drying has gained popularity as a sustainable method for reducing food waste and loss, especially perishable commodities such as vegetables (Estrada-Girón *et al.* 2024). Drying is a well-recognized procedure that extends the shelf life of vegetables by reducing their water activity, which helps slow microbiological activity and decrease material physicochemical changes. The drying process is a generally accepted method for vegetable preservation due to its effect in prolonging storage life, lowering transportation costs, and its potential in reducing the packaging needs (Mohammed *et al.* 2024).

Despite its potential, limited studies exist on the drying behavior and energy efficiency of chayote squash, particularly regarding the optimization of the drying process under controlled convective conditions. Hence, this study utilized convective drying to develop the dried chayote squash (*Sechium edule*). This research aimed to study the drying kinetics, effective moisture diffusivity, specific energy consumption, and color change of chayote squash (*Sechium edule*) as influenced by drying temperature and slice thickness, and to determine the optimum drying temperature and slice thickness.

MATERIALS AND METHODS

Material

This study utilized chayote squash (*Sechium edule*) obtained from All Fresh Fruit Store, Alam Sutera, Tangerang, Indonesia. The chayote squash was harvested 3 to 4 months after planting. The moisture content of fresh chayote was 94.84±0.15 g_w.100 g_s^{-1} (wet basis) or 18.41±0.58 g_w.g_{ds}^{-1} (dry basis).

Sample preparation

Slices were prepared with thicknesses of 3 and 6 mm using a bench slicer (Orion VS-1368, Indotara, Indonesia) and a diameter of 30 mm using a molder. The weight of fresh chayote for 3- and 6-mm thicknesses was 45.21±2.19 and 77.40±1.05 g, respectively.

Drying experiment

The research variables employed in this study are the various air-drying temperatures (50, 60, and 70 °C) and the slice thicknesses (3 and 6 mm). During the experiment, an average air velocity of 3 m.s^{-1}, and an average *RH* of 15% were measured. The chayote slices were put on the shelves of the dehydrator in a uniform single layer. The dehydrator dimensions were 320×390×250 mm (Wirastar FDH-6, Wiratech, Indonesia), and the dehydrator was turned on 30 min before each experiment run.

The moisture content was calculated based on the expected initial moisture content of the samples (obtained from a preliminary experiment) and the weight of the samples, which was measured every 20 min during the first hour of drying and then every 30 min until the process was complete. The drying process was stopped when the moisture content was predicted to fall below 14 g of water per 100 g of sample (g_w.100 g_s^{-1}) or 0.16 g of water per gram of dry solid (g_w.g_{ds}^{-1}). Afterward, the MC of the final sample was determined after the drying process was completed for the actual MC value. The measured responses included the dry and wet basis moisture content (MC) during the drying process, the specific energy consumption, and the sample color before and after drying. The experiment employed a completely randomized design and was carried out with two replicates, resulting in 12 experimental runs. The optimal condition was computed using JMP® Pro (version 18.0.2, JMP Statistical Discovery LLC, Cary, NC, USA).

Drying time (DT), moisture content (MC), and moisture ratio (MR)

Moisture content (MC) calculation using Equation 1 (g water/g dry solid−$g_w.g_{ds}^{-1}$).

$$MC=\frac{W_i-W_e}{W_e} \quad (1)$$

MC determination of the final sample was performed using the method described by Md Saleh (2019) with modification. W_i and W_e are the sample weights (PA214, Ohaus, China) before and after being dried in an oven (UF 55, Memmert, Germany) at 105 ºC overnight. A dimensionless moisture ratio (*MR*) of chayote drying was expressed using Equations 2–3.

$$MR=\frac{MC_t-MC_e}{MC_0-MC_e} \quad (2)$$

MC_e (MC at equilibrium) is negligible compared to MC_t (MC at time t) and MC_0 (MC at time 0) during long-term drying (Faal *et al.* 2015); Thus, Equation 2 was modified.

$$MR= MC_t/MC_0 \quad (3)$$

Drying kinetics and model fitting

The drying kinetics of each experimental run were determined by plotting drying time against the moisture ratio, and the drying experiments were modeled using 11 commonly used thin-layer drying mathematical models (Faal *et al.* 2015), as presented in Table 1. Non-linear regression analysis was performed, and the model coefficient was calculated using the column formula function in JMP® Pro software version 18.0.2 (JMP Statistical Discovery LLC, Cary, NC, USA). The model with the lowest Sum of Squared Errors (SSE) was chosen at a significance level of 0.05 to determine the best-fitted model (Motulsky and Ransnas 1987). SSE was calculated using Equation 4.

$$SSE = \sum_{i=1}^{n}\left(MR_t-\widehat{MR}_i\right)^2 \quad (4)$$

Where $\widehat{MR}_i$ is the predicted moisture ratio.

Specific energy consumption (SEC)

Total energy consumption (TEC) (kJ) was calculated using Equation 5 (Beigi 2016).

$$TEC = A\times v\times \rho_a\times c_a\times \Delta T\times DT \quad (5)$$

TEC (kJ) represents the total energy required for drying; A (m^2) is the tray area; ν ($m.s^{-1}$) is the air velocity; ρ_a ($kg.m^{-3}$) is the air density; c_a ($kJ.kg^{-1}.^oC^{-1}$) is the specific heat; ΔT (ºC) is the temperature difference to the ambient temperature; DT (s) is the total drying time. Meanwhile, specific energy consumption (SEC) is defined by Equation 6.

$$SEC= TEC/W_0 \quad (6)$$

SEC refers to specific energy consumption ($kJ.kg^{-1}$), and W_0 is the fresh chayote weight (kg).

Table 1. Mathematical models used to fit the drying kinetics of chayote slices (Faal *et al.* 2015)

No.	Mathematical Model	Mathematical Model Formula
1	Lewis	$MR=e^{(-kt)}$
2	Page	$MR=e^{(-kt^n)}$
3	Modified Page	$MR=e^{(-kt)^n}$
4	Wang and Singh	$MR=1+at+bt^2$
5	Henderson and Pabis	$MR=ae^{(-kt)}$
6	Logarithmic	$MR=ae^{(-kt)}+c$
7	Approximation of Diffusion	$MR=ae^{(-kt)}+(1-a)e^{(-kbt)}$
8	Modified Page Equation-II	$MR=e^{\left(-c\left(\frac{t}{L^2}\right)^n\right)}$
9	Midilli and others	$MR=ae^{\left(-k(t^n)\right)}+bt$
10	Verma and others	$MR=e^{(-kt)}+(1-a)e^{(-gt)}$
11	Modified Henderson and Pabis	$MR =ae^{(-kt)}+be^{(-gt)}+ce^{(-ht)}$

Effective moisture diffusivity (D_{eff})

Fick's second law can be used to define the effective moisture diffusivity (D_{eff}) of a slab. Within this study, we assumed that the initial moisture is distributed evenly, external resistance and shrinkage are negligible, diffusivity and temperature are constant, and only the first term is considered during long-term drying (Nguyen and Le 2022) as described by Equation 7.

$$\ln MR = \ln\left(8/\pi^2\right) - \left(\pi^2 D_{eff}/4L^2\right)DT \quad (7)$$

Hence, the D_{eff} ($m^2.s^{-1}$) can be computed from the slope of the plot of ln MR and DT, where L refers to half the thickness of the sample in meters (m).

Activation energy (E_a)

The activation energy can be determined using the Arrhenius equation, as shown in Equation 8 (Aral and Beşe 2016).

$$k =k_0\, e^{(-E_a/RT)} \quad (8)$$

The Arrhenius model for chayote drying can be obtained by plotting the natural logarithm of the effective diffusivity coefficient (D_{eff}) against the inverse of the drying temperature (T^{-1}). In this model, k is replaced by D_{eff}, and k_0 is replaced by D_0, representing the pre-exponential factor ($m^2.s^{-1}$). R is the universal gas constant ($8.3142\ kJ.mol^{-1}$), and T is the temperature in Kelvin. The activation energy (E_a, kJ.mol^{-1}) can be determined from the slope of the ln D_{eff} versus T^{-1} plot.

Chromaticity

Chayote slice chromaticity was recorded using a portable colorimeter (NH310, 3NH, China) before and after the drying process. The colorimeter was calibrated using a standard white plate before measuring the samples. The chromaticity indices (L*, a*, and b* values) were measured in triplicate to calculate the total color difference (ΔE^*_{ab}) (Md Saleh *et al.* 2019) as seen in Equation 9.

$$\Delta E^*_{ab} = \sqrt{\left(L^*_f - L^*_0\right)^2 + (a^*_f - a^*_0)^2 + \left(b^*_f - b^*_0\right)^2} \quad (9)$$

Within this equation, lightness coordinate–L*, red or green coordinate–a*, blue or yellow coordinate–b*, and total color difference–ΔE^*_{ab}. Subscript 0 indicates the initial value of the parameter, and subscript f indicates the value of the parameter at the end of the drying.

Data analysis

All analytical data are presented as mean ± standard deviation. The data were statistically analyzed using JMP® Pro software version 18.0.2 (JMP Statistical Discovery LLC, Cary, NC, USA). One-way analysis of variance (ANOVA) was performed at a significance level of 5%, followed by Tukey's test to determine significant differences among treatments.

Availability of data and materials

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

RESULTS AND DISCUSSION

Drying kinetics of chayote slices

All twelve experiment runs to observe the drying kinetics were modeled with the selected eleven mathematical models as presented in Table 1. As indicated by the lowest SSE, four experiment runs (3 and 6 mm at 50 °C) of chayote drying kinetics follow the mathematical model of diffusion approximation, while the remaining eight experiment runs (3 and 6 mm at 60 and 70 °C) follow the model of Midilli and others. The complete model fittings are presented in the supplementary material.

This result is different from those found in other studies. Álvarez-Morales *et al.* (2019) found that the drying kinetics of the chayote slice (5 mm, 60 °C, 240 min) followed the polynomial model. In comparison, Estrada-Girón *et al.* (2024) suggested that the parabolic model for thin-layer materials provides the best fit for composite-coated chayote slices (2 mm, 65 °C, until MC was constant). Meanwhile, Akonor and Tortoe (2014) found that the mathematical model best fitted with untreated chayote slices (4 mm, 65 °C, 420 min) is the Henderson and Pabis model. These discrepancies are likely due to the use of different mathematical model sets utilized for model fitting or differences in experimental methods, such as coating preparation and drying conditions. Siqueira *et al.* (2020), who studied the buckwheat grain drying process, mentioned that different drying temperatures had different best-fit mathematical models. In their study, the Midilli model is suitable for drying processes conducted at temperatures of 40, 60, and 70 °C, while an approximation of the diffusion model fits best for temperatures of 50 and 80 °C. The results of Siqueira *et al.* (2020) 's study align with the current study's findings.

Figure 1 captures the models with their corresponding experiment runs. All conditions exhibit an exponential MR decrease over time, which is characteristic of thermal drying processes. The sharp decline in MR during the initial stages indicates the rapid evaporation of surface moisture, followed by a slower drying phase where internal diffusion becomes the limiting factor (Berk 2018).

Drying time, total color difference, and specific energy consumption of chayote slices

The mean final moisture content across all experimental runs was 13.47±1.38 $g_w.100\ g_s^{-1}$ for wet and 0.16±0.02 $g_w.g_{ds}^{-1}$ for dry basis. Table 2 exhibits the drying time, total color difference, and specific energy capacity of chayote slices.

As expected, the treatment with the highest temperature and the lowest thickness (70 °C, 3 mm) had the shortest drying duration, while the treatment with the lowest temperature and the highest thickness (50 °C, 6 mm) had the longest drying duration (Kamal *et al.* 2023). Schemminger *et al.* (2024) found that thinner slices heat up more quickly by reaching the equilibrium state of convective heat transfer from the air to the slice, combined with the evaporative cooling effect. This finding aligns with the results of the present study as well. Regarding the effect of temperature on drying time, Doymaz *et al*. (2018) mentioned that greater heat absorption raises the product's temperature, which increases the driving force for mass transfer; as a result, moisture was driven out more quickly, leading to faster drying and reduced drying times. Álvarez-Morales *et al.* (2019) reported an average drying time of 240 min for chayote slices (5 mm, 60 °C, until a_w reached 0.6). This result is comparable to our samples, which were dried at the same temperature with thicknesses of 3 and 6 mm.

The color of raw and processed foods is a crucial aspect that significantly influences consumer food selection and acceptance (Imchen and Singh 2023). The chromaticity indices for fresh and dried chayote are presented in Table 3. The results show that, in general, all samples exhibited an increase in yellowness (b*) values after drying, which may be attributed to the increase in the concentration of carotenoids due to the loss of moisture and the degradation of chlorophyll, as well as potential chemical reactions, such as Maillard reactions (Salehi and Kashaninejad 2018). There is no significant change observed in the lightness and the redness between fresh and dried chayote squash. Hence, the rise of b*, which likely contributed to the increase of ΔE^*_{ab}.

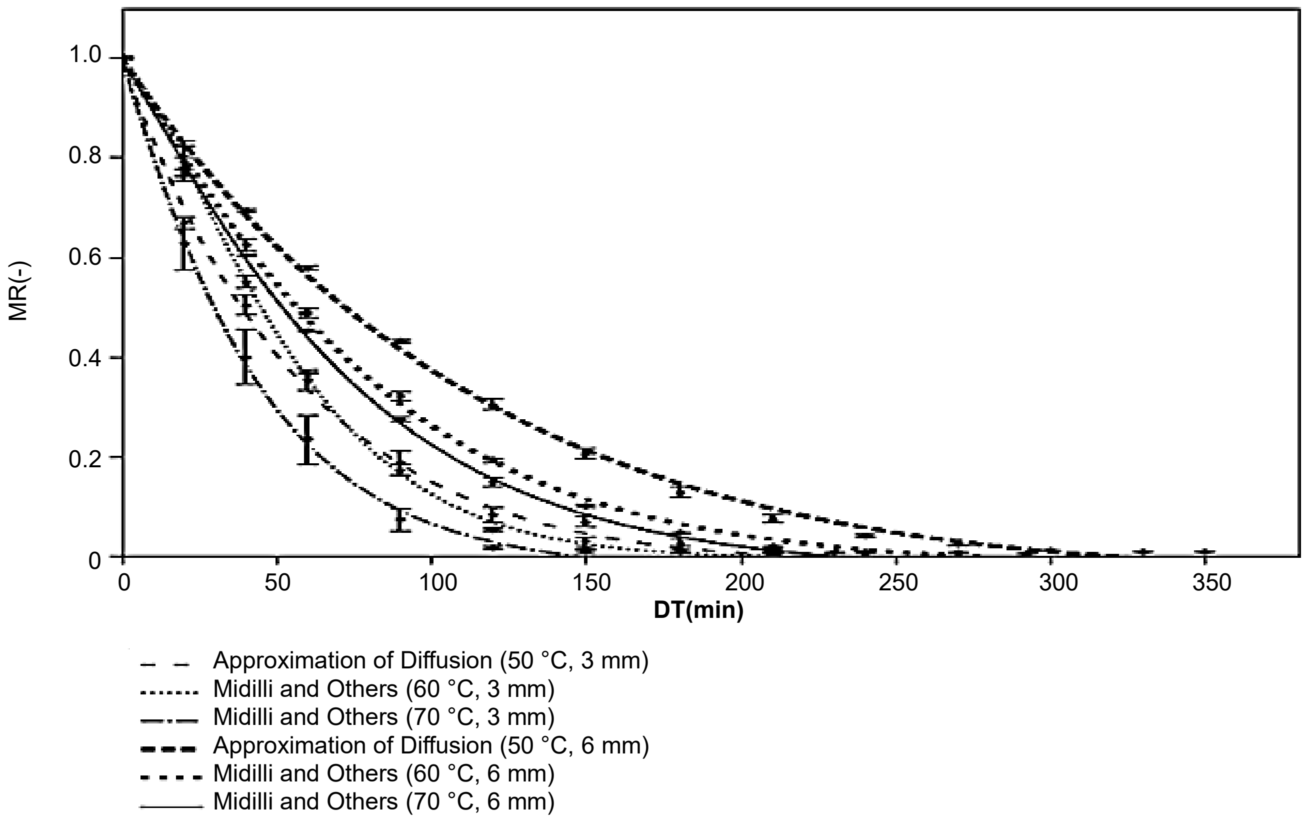

Figure 1. The drying kinetics of experimental runs and their corresponding best-fit models

Table 2. Drying time, total color difference, and specific energy capacity of chayote slices

Treatment	DT (min)	ΔE^*_{ab} (-)	SEC (kJ.kg^{-1})
50 °C, 3 mm	230±14.14^{c}	16.08±2.44^{a}	2.83x10^{6} ±2.35x10^{5b}
60 °C, 3 mm	210±0.00^{c}	18.05±2.47^{a}	3.40x10^{6}±1.89x10^{5a}
70 °C, 3 mm	150±0.00^{d}	16.65±3.22^{a}	2.87x10^{6}±1.35x10^{5ab}
50 °C, 6 mm	350±14.14^{a}	16.13±3.75^{a}	2.43x10^{6}±5.27x10^{4b}
60 °C, 6 mm	292.5±10.61^{b}	15.99±2.80^{a}	2.76x10^{6}±1.30x10^{5b}
70 °C, 6 mm	240±0.00^{c}	14.84±1.86^{a}	2.78x10^{6}±8.10x10^{3b}

Note: $^{a-b}$ Numbers in the same column followed by different letters indicate a significant difference ata 95% confidence level (*p*<0.05)

Table 3. L*, a*, and b* values of chayote slices before (subscript 0) and after (subscript f) drying

Treatment	L^*_0	L^*_f	a^*_0	a^*_f	b^*_0	b^*_f
50 °C, 3 mm	72.35±2.64^{aA}	73.47±0.38^{abA}	-2.08±0.65^{aA}	-4.06±0.55^{aA}	12.22±1.12^{aB}	27.42±1.02^{aA}
60 °C, 3 mm	71.73±1.5^{aA}	76.57±1.64^{abA}	-2.17±0.32^{aA}	-3.94±0.73^{aA}	12.86±1.38^{aB}	29.60±0.27^{aA}
70 °C, 3 mm	71.53±4.84^{aA}	77.85±0.6^{aA}	-1.90±1.23^{aA}	-1.47±0.34^{aA}	10.16±0.07^{aB}	24.81±1.22^{aA}
50 °C, 6 mm	68.40±6.96^{aA}	74.98±3.40^{abA}	-1.47±0.14^{aA}	-0.98±1.17^{aA}	11.64±0.19^{aB}	25.83±2.59^{aA}
60 °C, 6 mm	71.77±1.41^{aA}	75.70±0.90^{abA}	-2.83±1.20^{aA}	-1.51±2.35^{aA}	12.56±1.57^{aB}	25.98±1.15^{aA}
70 °C, 6 mm	72.89±2.48^{aA}	68.97±0.54^{bA}	-2.95±0.93^{aA}	0.32±1.11^{aA}	13.70±0.07^{aB}	27.09±1.95^{aA}

Note: $^{a-b}$ Numbers in the same column followed by different letters indicate a significant difference at a 95% confidence level (*p*<0.05). $^{A-B}$ Numbers in the same row within each chromaticity index (L*, a*, b*), followed by different letters, indicate a significant difference at a 95% confidence level (*p*<0.05)

 DOI: 10.29244/jmpi.2025.12.2.141

Meanwhile, the ΔE^*_{ab} magnitude > 3 showed that, according to all experiment runs, dried samples exhibited a distinct color, different from that of fresh samples (Dattner and Bohn 2016). However, the resulting total color difference was not significantly different among samples with various drying temperatures and thicknesses. This result aligns with the findings of Guine *et al.* (2017) on the study of the drying process of eggplant, which showed no significant color difference among samples dried at various temperatures ranging from 50 to 80 °C. The moisture level of the dried samples influenced their reflectance-based color readings (Özkan *et al.* 2003). Additionally, the removal of water may alter the material's light-reflecting ability and cause shrinkage, which in turn modifies the surface structure of the material (Lewicki and Duszczyk 1998). The moisture content difference between fresh and dried samples in this study was similar among all experiment runs. This condition may be attained since the drying process was stopped when the targeted moisture content was reached. In general, the drying process takes longer at lower temperatures, resulting in prolonged exposure to heated air. This extended exposure to heated air accelerates pigment breakdown and browning reactions, leading to more pronounced color degradation (Md Saleh *et al.* 2019). However, in this study, the moisture content appeared to have a greater impact on color than the drying temperature and thickness.

The SEC values are presented in Table 2. Samples with a 3 mm thickness have relatively higher SEC values compared to those with a 6 mm thickness. Higher SEC values may have occurred due to the reduction in SEC, resulting from reduced energy use per unit mass (6 mm thickness samples had a higher mass than 3 mm thickness samples, resulting in a lower value of energy use per unit mass). At a thickness of 3 mm, SEC increased from 50 to 60 °C; however, SEC decreased as the temperature reached 70 °C. From 50 to 60 °C, the increase in SEC caused by high temperatures was more significant than the decrease in SEC caused by a shorter drying time at the same temperature. From 60 to 70 °C, on the other hand, the reduction in SEC caused by a shorter drying time at a high temperature was more significant than the increase caused by the same temperature. The results of these studies are consistent with those of other studies on the drying of cocoyam (Ndisya *et al.* 2020) and celeriac (Nurkhoeriyati *et al.* 2021). However, no significant difference was found in the SEC value for all drying temperatures in the 6 mm treatment. This event may be explained as follows: during these treatments, the variable of thickness is more sensitive to SEC than the drying temperature (Schemminger *et al.* 2024).

The authors have not found studies on energy consumption in chayote hot-air drying. However, a survey on vacuum drying at 54 to 66 °C of chayote slices (1, 3, and 5 mm in thickness) found lower energy consumption, ranging from 1.93×10^5 to 3.42×10^5 $kJ.kg^{-1}$ (Lalrammawii and Said 2023). This discrepancy in results may have occurred because hot air drying typically consumes more energy than vacuum drying, especially when drying at higher temperatures. Vacuum drying can achieve faster drying rates at lower temperatures, resulting in lower energy consumption (Le *et al.* 2025).

Effective moisture diffusivity and activation energy

Table 4 shows the D_{eff} and E_a obtained for chayote. The D_{eff} increases with temperature and sample thickness. Chayjan *et al.* (2013) also found similar results in the study of squash seed; as drying air temperatures increased for both semi-fluidized and fluidized bed conditions, D_{eff} values increased more intensively. Moreover, thicker samples have a higher volume-to-surface ratio, which enhances moisture distribution and accelerates moisture movement (Md Saleh *et al.* 2019). This result is comparable to the findings of Ruiz-López *et al.* (2010). They found that the D_{eff} values for the fresh chayote drying studies ranged from 3.66×10^{-9} to 4.05×10^{-9} $m^2.s^{-1}$. Another study on D_{eff} of chayote found higher values of 1.09×10^{-8} to 1.30×10^{-8} $m^2.s^{-1}$ which may have been achieved as the drying time (420 min) was significantly higher than that of in this study, therefore the chayote samples experienced enhanced moisture distribution and accelerate the moisture movement. Discrepancies in the results may be caused by various factors, including the types and varieties of commodities, parameter settings, and the type of drying equipment (Md Saleh *et al.* 2019).

Table 4. The coefficient of effective diffusivity and energy of activation for chayote slice drying

Treatment	D_{eff} ($m^2.s^{-1}$)	E_a ($kJ.mol^{-1}$)
50 °C, 3 mm	$3.38 \times 10^{-10} \pm 1.17 \times 10^{-11}$ f	
60 °C, 3 mm	$4.06 \times 10^{-10} \pm 1.61 \times 10^{-12}$ e	17.44±0.27
70 °C, 3 mm	$4.94 \times 10^{-10} \pm 2.03 \times 10^{-11}$ d	
50 °C, 6 mm	$8.64 \times 10^{-10} \pm 3.87 \times 10^{-12}$ c	
60 °C, 6 mm	$1.11 \times 10^{-9} \pm 1.19 \times 10^{-11}$ b	18.05±0.12
70 °C, 6 mm	$1.28 \times 10^{-9} \pm 2.06 \times 10^{-11}$ a	

Note: a-b Numbers in the same column followed by different letters indicate a significant difference at a 95% confidence level (p<0.05)

However, E_a values are not significantly different among thicknesses. Moderate thickness often alters moisture diffusivity, but the activation energy is not significantly altered, as E_a captures how temperature sensitivity varies, but not how quickly moisture exits (Chigbo *et al.* 2024). In addition, physical mechanisms such as edge diffusion, surface hardening, and moisture movement in multiple directions can equalize E_a across thicknesses (Kek *et al.* 2014). E_a can be extracted from the slope (E_a/R, the universal gas constant) of ln D_{eff} against the T^{-1} plot as shown in Figure 2.

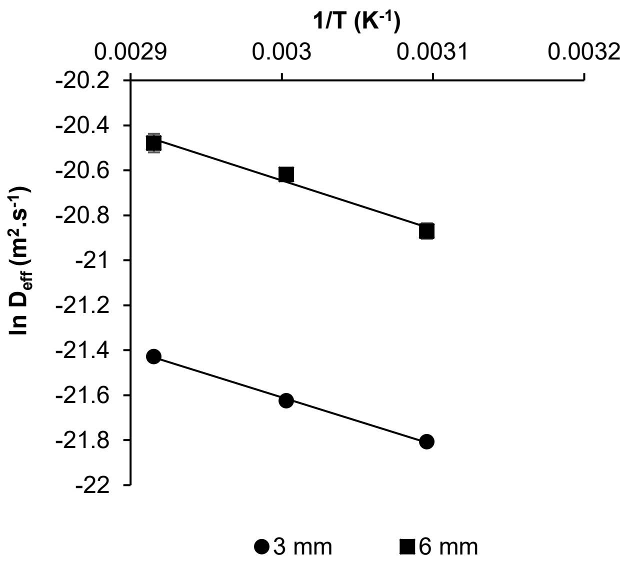

Figure 2. The Arrhenius model for chayote expresses the natural logarithm of diffusivity coefficients as a function of the drying temperature

Optimization

To determine the optimal drying temperature and thickness, we considered important factors for manufacturers (DT and SEC) and consumers (ΔE^*_{ab}), which should be minimized as much as possible. Energy consumption must be minimized to ensure the sustainability of resources for the production process (Ndisya *et al.* 2020). Furthermore, energy-efficient food processing could contribute to minimizing food loss and waste (Mwape *et al.* 2025). As shown in Figure 3, the optimum drying conditions, 70 °C, and a sample thickness of 3 mm are predicted to result in a drying time of 149 min, ΔE^*_{ab} value of 16.62, and an SEC of 3.02×10^6 kJ.kg^{-1}.

Convective dryers account for approximately 85% of industrial drying equipment. These conventional methods present opportunities for energy conservation by assessing energy-intensive steps and optimizing drying durations (von Gersdorff *et al.* 2018). Food products typically dried at temperatures ranging from 50 to 90° C, with relative air humidity between 10% and 40%, and air velocities of 1 to 4 m.s^{-1} (Krokida and Maroulis 2000). However, variations in these parameters can significantly affect the quality of the final product. Therefore, optimizing these drying parameters is essential to strike a balance between energy efficiency and product quality.

However, this current study has limitations, as optimization did not consider other quality attributes, such as the retention of bioactive compounds, sensory qualities, and microbial safety of chayote slices. Additionally, neither pre-drying treatments (e.g., blanching, acid dipping) nor measurement of drying parameters, such as variation in air velocity, were carried out in this study. These factors can be further investigated in future studies.

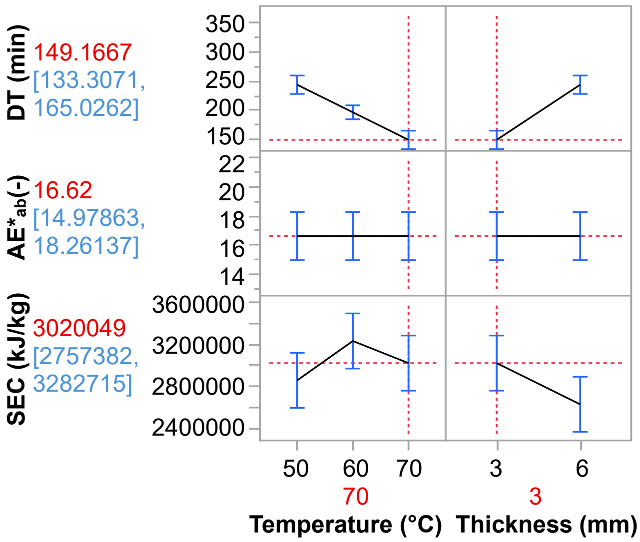

Figure 3. Profiler showing the relationship between each factor and the response

CONCLUSION

In conclusion, the approximation of diffusion and Midilli and others' models were the most accurate in describing the drying kinetics of chayote. Treatments with the highest temperature and the lowest thickness had the shortest drying times, while treatments with the opposite had the longest drying times. The 3 mm thickness at 60 °C had the highest specific energy consumption (SEC), while other samples showed no significant differences. Thicker samples resulted in lower SEC due to reduced energy use per unit weight. The effective diffusion coefficient (D_{eff}) increased with temperature and sample thickness, ranging from 3.38×10^{-10} to 1.28×10^{-9} m^2.s^{-1}, which is typical for agricultural products. However, activation energy (E_a) values were not significantly different among various thicknesses. Moreover, the color change (ΔE^*_{ab}) did not show significant differences across the samples. Finally, the optimal drying conditions to minimize drying time, ΔE^*_{ab}, and SEC were found to be 70 °C with a 3 mm slice thickness and are predicted to result in a drying time of 149 min, a ΔE^*_{ab} value of 16.62, and an SEC of 3.02×10^6 kJ.kg^{-1}.

ACKNOWLEDGMENTS

The authors acknowledge Bina Nusantara University for providing the facilities utilized during this study.

AUTHOR CONTRIBUTION STATEMENT

Tina Nurkhoeriyati: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Validation, Software, Writing – original draft, Writing – review & editing, Supervision, Resources, Project administration. Ignatius Arya Krishna Rustandi: Data curation, Formal analysis, Writing – review & editing. Mwewa Chikonkolo Mwape: Writing – review & editing, Visualization, Validation, Software, Data curation.

SUPPLEMENTARY MATERIAL

The supplementary material is presented in the following link: Supplementary material.xlsx

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