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Drying Kinetics of Banana Chips: A Modeling Approach

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ABSTRACT

The primary goal of this research is to identify and evaluate the most suitable thin-layer drying model to effectively interpret the drying characteristics of banana chips and determine moisture diffusivity at different drying temperatures. The study utilized physiologically mature "kapok" bananas from the local market in Jember Regency. A flash dryer with a 4000-watt electric heating system was used, equipped with a blower for air circulation, an exhaust fan to expel water vapor. The bananas were processed into chips with a thickness of 1 mm. A total of 2000 g of banana chips were dried at constant temperature according to treatment conditions (air velocity 3.2 m/s, drying at temperatures of 60, 70, and 80°C). The study found that higher drying temperatures (80°C) achieved the highest initial drying rate (35.9% in 30 min) compared to 60°C (28.0%) and 70°C (22.0%). However, the drying rate gradually decreased at all temperatures. The drying kinetics of banana chips at 60, 70, and 80°C aligned well with the modified Midilli model. Effective moisture diffusivity values for banana chips at 60, 70, and 80°C were 4.947E-9 m^2/s, $5.165(10^{-9})$ m^2/s, and $5.756(10^{-9})$ m^2/s, respectively, indicating that drying at 80°C was the most effective. The effective moisture diffusivity value showed a strong correlation with air velocity, drying temperature, material thickness, RH, and specific material attributes.

1. INTRODUCTION

Bananas are currently used in their fresh form or processed into traditional foods. However, there is potential to enhance their economic value by transforming them into banana flour. This flour is derived from chips of ripe bananas, which are dried into chips and then finely ground. The moisture content of the banana chips should be low, approximately 10 to 12%, and the flour yield ranges from 16.25 to 22.5%. Drying can be carried out either under sunlight or by using drying equipment, which tends to be more efficient. Using drying equipment offers the advantage of maintaining product quality and expediting the drying process at higher temperatures (de Farias *et al*., 2020). Studying the drying kinetics of bananas is crucial in determining the accurate operational conditions for the drying process. Drying kinetics involve a profound understanding of how the moisture content in bananas changes over time, considering particular factors like temperature, humidity, and the techniques employed for drying. By analyzing the drying kinetics, one can identify the optimal drying rate, determine the required time, and optimize parameters like temperature and air velocity to achieve the desired outcomes. This aids in avoiding over-drying or under-drying while maximizing the effectiveness of the drying procedure, which, in turn, supports the production of high-quality and sustainable banana flour (de Farias *et al*., 2020).

The thin-layer drying method is a noteworthy and significant technique for moisture removal, and its imperative importance is underscored by several compelling factors (de Farias *et al*., 2020). These factors encompass the enhancement of drying efficiency, product quality, and energy efficiency. Thin-layer drying distinguishes itself by effectively diminishing the moisture content in materials through the direct extraction of surface water. This method provides an advanced level of control over essential variables like temperature, duration, and humidity throughout the drying procedure. Within the contemporary landscape, characterized by an amplified emphasis on energy efficiency and environmental preservation, a profound understanding of thin-layer drying takes on a pivotal role in the pursuit of optimizing energy utilization during the drying process, ultimately resulting in reduced carbon emissions and operational expenditures (Pinheiro & Castro, 2023).

To refine the drying process to its best potential, a comprehensive understanding of the intricate dynamics during drying is crucial. This involves grasping fundamental elements like heat and mass transfer, drying kinetics, and the factors influencing the drying process. The versatility of thin-layer drying showcases its broad applications, from preserving diverse food items to its use in pharmaceutical production, agriculture, and semiconductor technology. The insights gleaned from mastering this method provide opportunities to customize and apply it to meet the diverse needs across various industries. The primary goal of this research is to pinpoint and assess the most fitting thin-layer drying model. This model aims to effectively interpret the drying characteristics of banana chips and ascertain the moisture diffusivity at different drying temperatures.

2. RESEARCH METHODS

2.1. Preparation

The material used was physiologically mature 'pisang kepok' bananas obtained from the local market in Jember Regency. The research utilized a flash dryer, driven by a 4000-watt electric heating system. The equipment was furnished with a blower for air circulation and an exhaust fan to aid in expelling water vapor from the drying chamber; a thermometer and hygrometer for measuring environmental conditions; an analytical balance, an oven for moisture content measurement; and Excel and MATLAB software for data processing and modeling.

2.2. Experimental Method

Bananas were prepared by blanching them in hot water for 10 minutes, peeling, and then slicing uniformly to a thickness of 1 mm to create chips. A total of 2000 grams of banana chips were arranged on the drying trays, with each tray containing 100 grams. The dryer was preheated to a constant temperature based on the treatment conditions (air velocity 3,2 m/s, drying at temperatures of 60, 70, and 80°C), and the drying process commenced according to the treatment parameters. Environmental air conditions were recorded (temperature and humidity). Moisture content was monitored every 30 minutes by weighing the samples during the 6-hour experiment.

2.3. Analysis

2.3.1. Moisture content

Moisture content is determined utilizing the equation for dry basis moisture content.

$$M = \frac{W(t)-d}{d}\ x\ 100\ \% \tag{1}$$

with *M* is dry basis moisture content, *W*(*t*) is material mass at given time *t*, and *d* = dry matter mass.

2.3.2. Drying rate

The drying rate, indicated as *DR* (% db/h), signifies the change in moisture content reduction within the sample throughout the drying process as time progresses. The following equation is used to calculate the drying rate.

$$DR = \frac{Mt-M(t+dt)}{dt} \tag{2}$$

where *Mt* is dry basis moisture content at time *t*, *M*(*t*+*dt*) is dry basis moisture content at time (*t* + *dt*), and *dt* is the observation time.

2.3.3. Moisture ratio

The moisture ratio (*MR*) is calculated using the following equation.

$$MR = \frac{Mt-Me}{Mo-Me} \tag{3}$$

with *MR* is moisture content ratio, *Mt* is moisture content at time *t* (db), *Me* is equilibrium moisture content, and *Mo* is initial moisture content of the material.

2.3.4. Moisture Diffusivity

Moisture diffusivity involves the motion of moisture within a material during drying. When the drying rate decreases, molecular diffusion becomes the primary factor in lowering water content. The effective diffusion coefficient is obtained by adapting a mathematical model of fluid diffusion using Fick's second law. This model assumes a plate-like shape, with moisture moving solely through diffusion, disregarding volume changes, while keeping a consistent temperature during extended drying periods.

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{\pi L^2}\right)t \tag{4}$$

From Equation (4), when values of (ln *MR*) are graphed against time to have a linear relationship with a specific slope.

2.3.5. Mathematical modelling

Mathematical models, fitness tests for observation results with models developed according to drying kinetics models Equation (5) to (13).

(1) Mod-Midilli Model

The Midilli model is employed when the initial moisture content matches the equilibrium moisture content at the start of drying. This requirement is met by adjusting the coefficient in the Midilli model to 1. Consequently, the modified Midilli model was evaluated using flax fiber and is formulated as follows (Farias *et al*., 2020; de Farias *et al*., 2020):

$$MR = a \exp(-k\, t^{n}) + b.t \tag{5}$$

(2) Page Model

This model is a revised version of the Lewis model, designed to address its limitations by introducing a dimensionless empirical constant (*n*) to the time component. This parameter moderates the time, resulting in improved predictions for moisture loss in this particular model (de Farias *et al*., 2020).

$$MR = \exp(-(k.t^{n})) \tag{6}$$

(3) Mod Page Model

Adjustments to the Page model are systematically employed and rigorously evaluated to faithfully represent the drying characteristics exhibited by a diverse range of agricultural products (de Farias *et al*., 2020).

$$MR = \exp(-(k.t)^{n}) \tag{7}$$

(4) Henderson – Pabis Model

The Henderson and Pabis model constitutes the introductory segment of a comprehensive series solution derived from the second law of Fick (Equation 8). Although this model is effective in predicting drying rates during the early stages of the drying process, its effectiveness may decrease at later stages. The drying process of African breadfruit seeds, bananas, mangoes, cassava, and onions was successfully modeled. The parameter *k* in this model is related to the effective diffusivity, especially if the drying process occurs mainly during the period of falling velocity and is mainly determined by the diffusion of the liquid (de Farias *et al*., 2020).

$$MR = a \exp(-k.t) \tag{8}$$

(5) Weibull – Distribution Model

This model has no clear physical basis and serves only as a statistical approach. An alternative model based on the Weibull distribution is described below. This model has been studied in the context of both fig drying and jujube drying (de Farias *et al*., 2020).

$$\text{Weibull – distribution I : } MR = a - b \exp[(-k.t^{n})] \tag{9}$$

$$\text{Weibull – distribution II : } MR = a \exp(-k.t^{n}) + b \tag{10}$$

(6) Lewis Model

Lewis proposed an analogy between moisture movement in agricultural materials and heat dissipation from an object in a cold liquid. The drying rate follows Newton's law of cooling and is based on the deviation between the existing moisture content and the equilibrium moisture content.

$$MR = \exp(-(k.t)) \tag{11}$$

This model simplifies the process by ignoring internal resistance and gradients and focusing on surface resistance. There is a tendency to underestimate later drying stages and overestimate early stages. Despite this limitation, it has been effectively used to study a variety of agricultural products such as strawberries, red chili peppers, grape seeds, and black tea (de Farias *et al*., 2020).

(7) Fick's Model

A simplified solution to Fick's diffusion equation is shown by Equation (12). This can be applied for longer drying times (Farias *et al*., 2020; de Farias *et al*., 2020; Pinheiro & Castro, 2023). This model was used to simulate the drying process of bay leaves, apricots and apples (Farias *et al*., 2020).

$$MR = ae^{\left(-c\left(\frac{t}{L2}\right)\right)} \tag{12}$$

(8) Wang and Singh Model

Wang and Singh introduced a new quadratic equation to model paddy rice monolayer data (Farias *et al*., 2020). This equation was successfully applied to describe the drying properties of banana parsley leaves and bamboo shoot chips (de Farias *et al*., 2020).

$$MR = 1 - a\,t + b\,t^{2} \tag{13}$$

2.3.6. Fitting model

Model accuracy analysis is performed to determine the optimal model equation based on experimental results. Accuracy metrics used include the coefficient of determination (R^2). Root mean square error (RMSE) is a measure of the variance of the residual data (prediction error) in the model. and sum of squared errors [SSE], SSE provides information about how much the observed data deviate from the regression line or prediction model. A lower SSE value indicates that the model better explains the variation in the data. Each is calculated using the following formulas (Equations 14, 15, and 16):

$$R^2 = \frac{\sum_{i=1}^{N}(MR_i - MR_{pre,i}).\sum_{i=1}^{N}(MR_i - MR_{pre,i})}{\sqrt{\left[\sum_{i=1}^{N}(MR_i - MR_{pre,i})^2\right]\left[\sum_{i=1}^{N}(MR_i - MR_{pre,i})^2\right]}} \tag{14}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N}} \tag{15}$$

$$SSE = \sum_{i-1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2 \tag{16}$$

3. RESULTS AND DISCUSSION

3.1. Moisture Content

The initial moisture content of the banana undergoing drying ranges from 64 to 66% (db, w/w). Figure 1 illustrates that the most rapid decline in moisture content, approximately 5% (db, w/w), occurs within 6 hours at a drying temperature of 80°C. The specific energy consumption for drying at 80, 70, and 60°C is 26,580, 31,420, and 36,770 kJ/kg H_2O, respectively. This data holds significant importance in comprehending the energy demands and efficiency variations across different drying temperatures. It enables the evaluation of the energy required to achieve the desired moisture reduction in the food material, offering valuable insights for enhancing the drying process and reducing energy consumption.

In a study conducted by Sam-Amoah (El-Wahhab *et al*., 2023) on drying banana fruit using a cabinet dryer, it took 15 hours to reduce the moisture content from 75 to 20%. Additionally, the continuous drying rates at temperatures of 80, 70, and 60°C were determined to be 8.3, 7.7, and 7.3% moisture content (db, w/w) per hour, respectively. This study shows how drying temperature affects the drying rate of banana chips, with the fastest decrease in moisture content occurring at 80°C, with a decrease of approximately 50% (w/w) within 6 h.

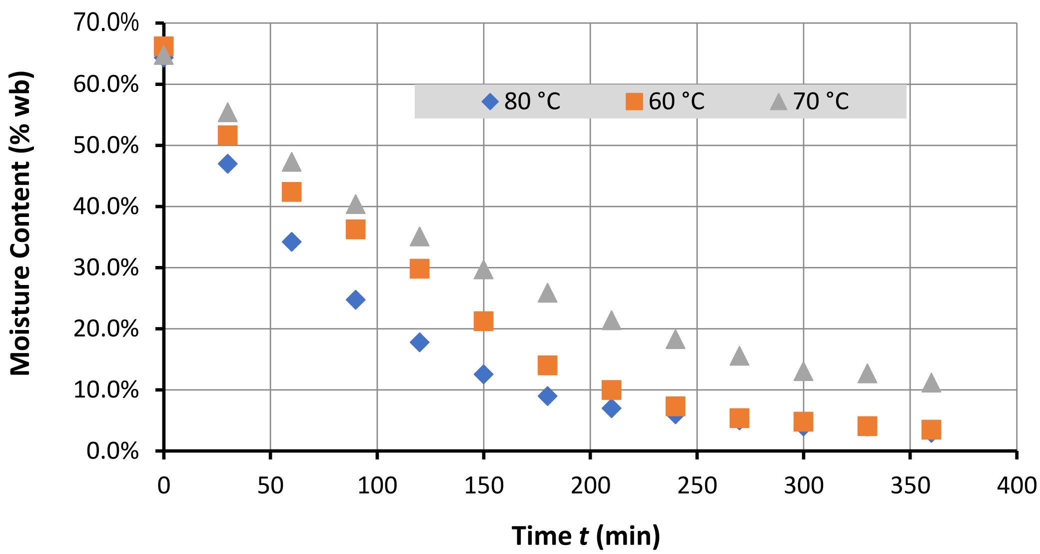

Figure 1. Moisture content reduction during the drying process.

Furthermore, this study found that the moisture diffusivity increased with increasing temperature, indicating a significant influence of temperature on the drying process. These findings highlight the importance of understanding the effects of food drying kinetics and temperature on food drying properties. Generally, this study shows a consistent trend of decreasing moisture content during the drying process. This observation is consistent with previous studies on banana slice drying, indicating the influence of drying temperature on the drying rate. The decrease in moisture content during drying is correlated with the drying rate and shows a pattern of moisture loss due to diffusion (Erol, 2022). Fluctuations in temperature during drying affect the ambient humidity and ultimately the drying rate of banana chips (Prachayawarakorn *et al*., 2008; Surendhar *et al*., 2019; Kadam, 2011). Moreover, the heat transfer caused by the drying temperature simultaneously affects the mass transfer, accelerating the evaporation process and leading to a significant decrease in moisture content during drying (El-Wahhab *et al*., 2023). Additionally, the shape of banana chips influences the drying rate, with chip chips drying faster compared to thick cubed chips (Ashaolu & Akinbiyi, 2015). Therefore, determining the optimal drying temperature can accelerate the drying process of banana chips and significantly influence the properties of the resulting dried product.

3.2. Drying Rate

The research findings indicate that as the drying temperature rises, so does the drying rate initially, followed by a subsequent decline across all temperature levels. This observation is corroborated by various studies on banana slice drying, underscoring the significant impact of drying temperature on the drying rate. Variations in drying air temperatures influence the ambient humidity during drying, thereby affecting the drying rate of banana chips (Atares *et al*., 2011; Taskin *et al*., 2022; Sarpong *et al*., 2018). Furthermore, the heat transfer resulting from the drying temperature affects mass transfer simultaneously, expediting the evaporation process and causing a substantial reduction in moisture content during drying. Additionally, the shape and thickness of the banana chips are contributory factors to the drying rate, with chip chips exhibiting faster drying compared to thicker and diced chips (Sarpong *et al*., 2018; Kushwah *et al*., 2022; da Silva Júnior *et al*., 2017). Hence, it can be deduced that higher drying air temperatures prompt increased moisture loss and quicker drying rates for banana chips.

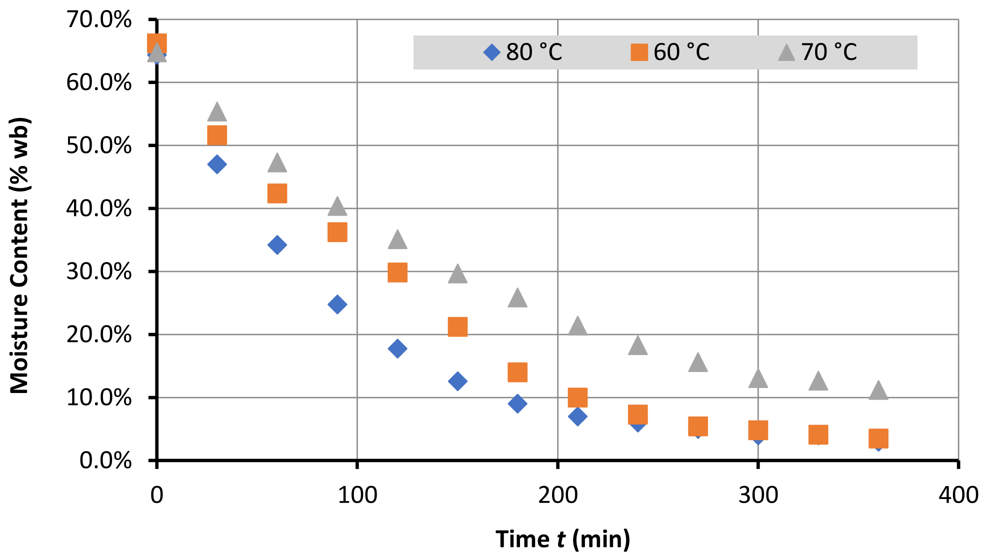

Figure 2. Drying rate for several levels of drying temperature

The graph depicted in Figure 2 shows that higher drying temperatures (80°C) achieve the highest initial drying rate (35.9% in 30 minutes) compared to 60°C (28.0%) and 70°C (22.0%), but the drying rate gradually decreases at all temperatures. Although higher temperatures reach lower moisture levels more quickly, all temperatures eventually reach similar moisture levels at the end of the drying process (1.0% to 2.0% in 360 minutes). The drying process for various food materials, such as banana chips, typically undergoes a phase referred to as the falling rate period. This phase is characterized by an initial rapid drying rate, succeeded by a gradual decline until the process concludes. Similar behavior has been observed in studies involving diverse food products like seaweed, lemon, and pomegranate (Atares *et al*., 2011). The decrease in the drying rate is attributed to the slow diffusion of bound water to the material's surface, occurring at a slower pace than free water. This phenomenon aligns with the concept of the falling rate period, consistent with Fick's Second Law of Diffusion. The drying rate, as evidenced in experimental studies on banana chips and other food items, is influenced by various factors, including temperature, loading density, and material thickness (Türkan & Etemoglu, 2020; Tekin *et al*., 2017).

3.3. Drying Kinetics

This study aimed to develop nine mathematical drying models, represented in Equations (5) to (13), to simulate the drying behaviors of banana chips across various drying temperatures. Moisture content measurements were utilized to calculate the moisture ratio (MR) value, aiding in the determination of the most appropriate model parameters.

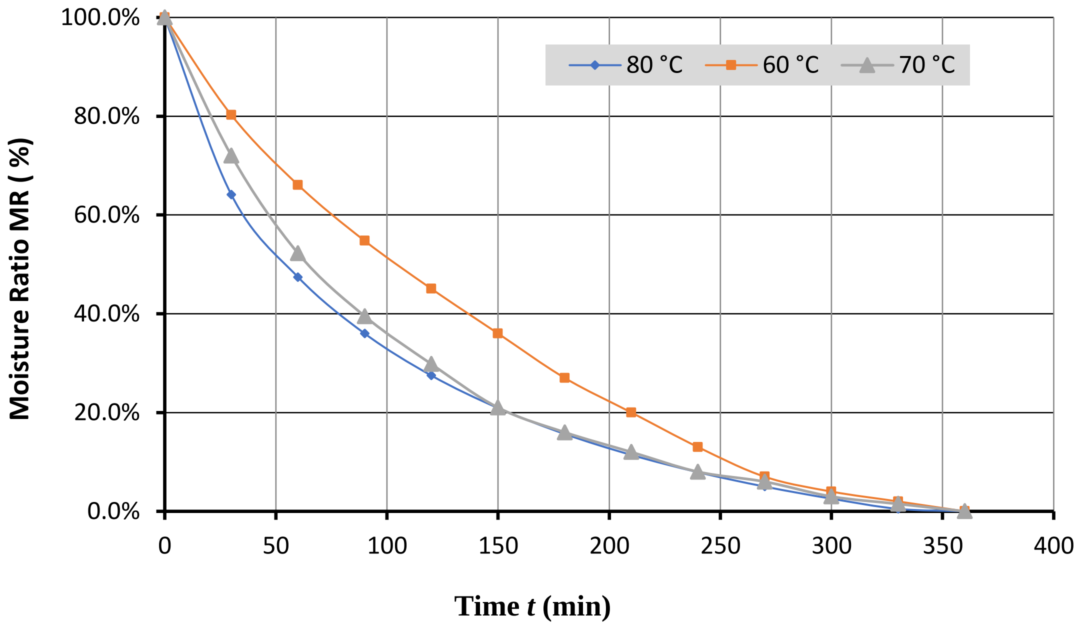

Figure 3. Drying characteristics of banana chips at various drying temperatures

Figure 3 displays the drying characteristics of banana chips at different drying temperatures, aligning with similar studies that employ mathematical models to analyze drying behaviors in various food materials such as carrots, ginger, corn kernels, and seaweed. These models serve to comprehend drying kinetics and forecast the impact of temperature on water diffusion within food substances. The modeling process was executed to identify the most fitting model, elucidating the dynamics of moisture content changes over time in line with Equations (5) to (13). This process sought to ascertain model parameters or constants that yield the least possible error (SSE and RMSE values) and the highest coefficient of determination (R^2).

The precision measures employed encompass the coefficient of determination (R^2), Root Mean Squared Error (RMSE), and Sum of Squared Error (SSE). RMSE gauges the dispersion of residual data (prediction errors) within a model, while SSE reveals the extent to which observed data deviates from the regression line or prediction model. A lower SSE value signifies a better explanatory model for data variance. These metrics are commonly used to appraise the performance of drying kinetics models and to identify model parameters or constants that minimize errors and maximize the model's explanatory capacity. Such evaluations are pivotal for comprehending the models' efficacy in capturing the dynamics of moisture content changes over time and optimizing the drying process.

The modeling process revealed that across all levels of drying temperatures, the Midilli-Modification model demonstrated the highest level of accuracy, evident from the R^2, SSE, and RMSE values in Table 1. Specifically, at drying temperatures of 60°C, 70°C, and 80°C, the Midilli-Mod model proved to be the most suitable for describing the drying process, showcasing the highest R^2 values of 0.998, 0.999, and 0.998, respectively. Analysis indicated that this model exhibited the smallest SSE and RMSE values, signifying minimal residual error and the lowest root mean square error. This indicates the model's exceptional precision and effectiveness in predicting the moisture content of dried material at different drying durations. These metrics play a critical role in evaluating the model's accuracy and dependability in forecasting the drying process and its outcomes.

Studies by (Kucuk *et al*., 2014a) demonstrate the Midilli-Modification model's suitability in modeling thin-layer drying processes for diverse food materials like bananas, taro, garlic, and Chinese dates. This highlights the adaptability and applicability of this model across various food materials, showcasing its potential practical utility within the food drying industry. Implementing this model could offer valuable insight into the drying kinetics of diverse

Table 1. Summary of drying kinetic models for bananas chips

Kinetic Model	Equation	Temp (°C)	Constant *a*	*b*	*c*	*k*	L_2	*n*	R^2	SSE	RMSE
Modified-Midili	$MR = a\exp(-k\,t^n) + b.t$	60	1.00	–0.01		0.61		1.01	0.998	0.0023	0.0133
		70	1.01	–0.01		0.71		0.74	0.999	0.0008	0.0110
		80	1.00	–0.01		0.70		0.86	0.998	0.0024	0.0139
Page	$MR = \exp(-(k.t^n))$	60				0.63		1.08	0.997	0.0045	0.0187
		70				0.74		0.88	0.967	0.0046	0.0196
		80				0.73		1.03	0.987	0.0048	0.0206
Modified Page	$MR = \exp(-(k.t)^n)$	60				0.65		1.08	0.997	0.0045	0.0187
		70				0.71		0.88	0.996	0.0046	0.0191
		80				0.70		0.90	0.996	0.0047	0.0194
Henderson –Pabis	$MR = a\exp(-k.t)$	60	1.01			0.67			0.995	0.0061	0.0217
		70	0.66			0.96			0.996	0.0058	0.0206
		80				0.66			0.995	0.0055	0.0196
Weibull I	$MR = a - b\exp[(-k.t^n)]$	60	–0.14	–1.14		0.62		0.71	0.997	0.0160	0.0351
		70	–0.14	–1.14		0.62		0.71	0.995	0.0351	0.0000
		80	–0.14	–1.14		0.61		0.73	0.996	0.0000	0.0000
Weibull II	$MR = a\exp(-k.t^n) + b$	60	–0.05	–1.04		0.59		0.99	0.998	0.0021	0.0127
		70	–0.05	–1.04		0.59		0.99	0.998	0.0127	0.000
		80	–0.05	–1.04		0.61		0.73	0.998	0.0000	0.0000
Lewis	$MR = \exp(-(k.t))$	60				0.66			0.996	0.0063	0.0220
		70				0.68			0.997	0.0061	0.0215
		80				0.68			0.997	0.0062	0.0216
Fick's Model	$MR = ae^{(-c(\frac{t}{L2}))}$	60	1.01		0.77		1.16		0.996	0.0061	0.0217
		70	0.96		0.76		1.14		0.998	0.0059	0.0209
		80	0.96		0.76		1.16		0.997	0.0060	0.0213
Wang and Singh	$MR = 1 - a\,t + b\,t^2$	60	0.44	0.05					0.986	0.0026	0.0044
		70	0.44	0.05					0.995	0.0025	0.0043
		80	0.44	0.05					0.996	0.0025	0.0044

food products, contributing significantly to optimizing drying procedures and achieving specific drying objectives. These findings imply that the Midilli-Modification model is a robust tool with broad applicability, making it a valuable asset for enhancing efficiency and precision in food drying practices (Kucuk *et al*., 2014b). Figure 4 illustrates the alignment between the experimental and predicted moisture ratio values, both following a similar trajectory, as observed in the Midilli-Modification Model.

The practical application of the developed mathematical model is deemed to have significant potential in predicting the moisture content of banana chips throughout various drying durations, providing valuable insights into the kinetics of the drying process. This model is seen as a pivotal tool in optimizing the overall drying process for banana chips, enabling improved control and alignment with specific process objectives. The utilization of mathematical models to forecast moisture content at different drying intervals is considered imperative for the advancement of the efficiency and quality of the drying procedure.

These models are regarded as instrumental tools in comprehending the intricate drying behavior and the mechanism of moisture transfer. Through this understanding, contributions are made to an enhanced comprehension of the process dynamics, leading to improved product characteristics and heightened control over the overall drying process. In essence, the use of mathematical models in predicting moisture content during various drying stages is seen as a strategic approach to achieving precision, efficiency, and quality in the banana drying process

The Midilli-Modification model has been found to be applicable beyond food drying, as evidenced by its use in various industries. For instance, it has been effectively employed in the drying of wet-processed parchment coffee, demonstrating its adaptability to coffee drying processes (Kucuk *et al*., 2014b). Additionally, the model has been utilized in the thin-layer drying of red pepper chips, indicating its potential for application in the drying of a diverse range of agricultural products. Furthermore, the model has been discussed in the context of drying techniques for food

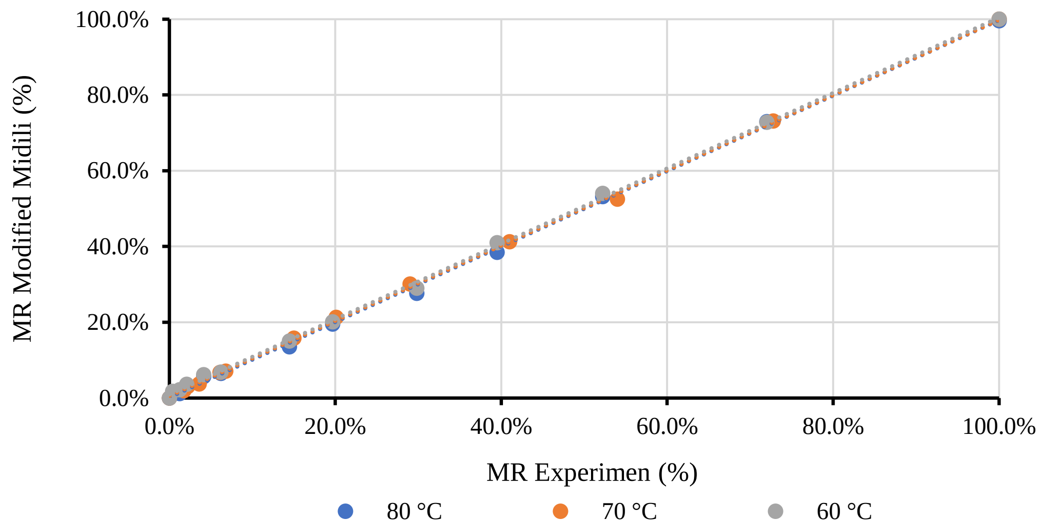

Figure 4. Relationship of moisture ratio (MR): Experiment vs. the modified Midilli model.

materials, highlighting its relevance in addressing moisture reduction and shelf-life extension in food preservation. These instances illustrate the versatility of the modified-Midilli model, suggesting its potential for broader application in industries beyond food drying (Prachayawarakorn *et al*., 2008).

3.4. Effective Moisture Diffusivity

During drying, effective moisture diffusivity signifies the inward movement of water within a substance towards the surface, prompted by fluctuations in water vapor pressure. Fick's Second Law of Diffusion is applied to clarify this process, particularly during the phase of decreasing drying rate. The determination of effective moisture diffusivity (Deff) involves using the slope method, where the logarithm of the moisture ratio (*ln* MR) is graphed against drying time (*t*) based on experimental data for each treatment in the drying methods (Da Silva et al., 2014) (Tortoe et al., 2007). Figure 5 presents a graph of (*ln* MR) vs. time (*t*) based on our experiment results.

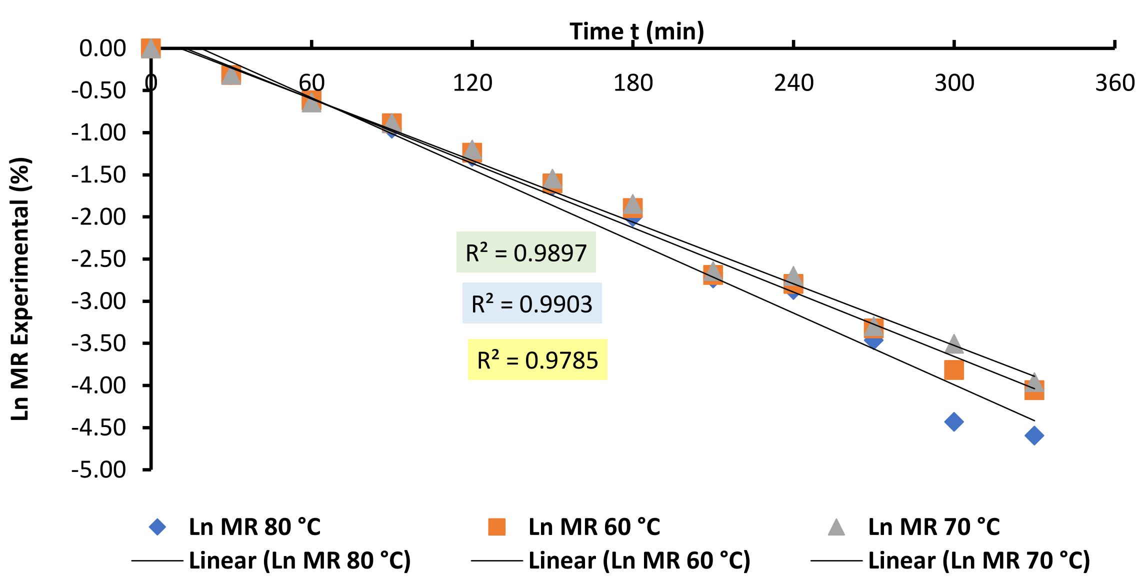

Figure 5. Plot of *ln MR* (%) vs time *t* (min)

Table 2. The values of effective moisture diffusivity (*Deff*) at various drying temperatures

Drying Temperature	Deff (m^2/s)	R^2
60°C	4.947 E-09	0.9903
70°C	5.165 E-09	0.9897
80°C	5.756 E-09	0.9785

Differences in *Deff* values among treatments are impacted by multiple factors, including temperature, size, material thickness, and others.

Table 2 presents the effective moisture diffusivity (*Deff*) values obtained through slope method analysis for the three drying treatments investigated in this study. The R^2 value in Table 2 indicates a strong linear correlation between ln MR and drying time (t) across all examined drying methods. The analysis reveals that the Deff values acquired fall within the typical range observed for various food materials, ranging from 10^{-12} to 10^{-8} m^2/s.

The effective moisture diffusivity (*Deff*) serves as a crucial parameter in the drying process of diverse materials, including banana chips. Its value is influenced by multiple factors, with drying temperature being a significant determinant. Studies suggest that higher drying temperatures are associated with greater *Deff* values. However, the statistical significance of this influence requires further investigation. Besides drying temperature, other factors such as drying air velocity, material thickness, relative humidity, and specific material properties also impact *Deff* values. Research indicates that both air flow velocity and drying temperature notably affect drying parameters. For instance, increased air velocity and drying temperature are linked to higher drying rates and an overall increase in moisture transfer coefficient. Additionally, experiments conducted at various drying air temperatures and superficial fluidization velocities have provided valuable insights into the relationship between these variables and Deff values (Tortoe et al., 2007) (Dadmohammadi & Datta, 2020) (Kayacier & Singh, 2004).

4. CONCLUSIONS

According to the findings of this study, it was determined that higher drying temperatures (80°C) achieve the highest initial drying rate (35.9% in 30 min) compared to 60°C (28.0%) and 70°C (22.0%). However, the drying rate gradually decreases at all temperatures. The kinetics of the banana chips drying process at temperatures of 60, 70, and 80°C effectively align with the Modified Midilli model. The effective moisture diffusivity values for banana chips at 60, 70, and 80°C are 4.947E-9 m^2/s, 5.165E-9 m^2/s, and 5.756E-9 m^2/s respectively, indicating that drying at 80°C is the most effective. The Effective Moisture Diffusivity (Deff) value demonstrates a strong correlation with drying temperature, air velocity, material thickness, relative humidity, and specific material attributes.

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