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MATHEMATICAL MODELLING OF DEHYDRATOR DRYING ON APPLE FRUIT SLICES

PEMODELAN MATEMATIS PENGERINGAN DEHIDRATOR PADA IRISAN BUAH APEL

Indah Yuliasih[1)*], Dzulkifli Rasyid[1)], and Niken Ayu Permatasari[2)]

[1)]Department of Agricultural Industrial Technology, Faculty of Agricultural Technology,
IPB University, IPB Dramaga Campus, Bogor, 16680
[2)]Division of Quality and Sensory of Plant Products, Department of Crop Sciences,
Georg-August-Universität Göttingen, Göttingen, Germany
Email : indahyuliasih@apps.ipb.ac.id

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ABSTRAK

*Penelitian ini dilakukan untuk mengevaluasi proses pengeringan menggunakan pendekatan model pengeringan Moisture Ratio (MR) antara lain model Newton, Page, Henderson-Pabis, dan Midili. Proses pengeringan lapisan tipis menggunakan food dehidrator Wirastar FDH10 pada suhu konstan 60°C selama 23 jam. Parameter yang diamati selama proses pengeringan yaitu penurunan bobot, kadar air, dan aktivitas air (a_w). Analisis data dan pemodelan matematika dilakukan dengan Microsoft Excel Analysis Tools Solver Add-In. Berat akhir irisan apel kering berkurang sebesar 80,2% dan kadar air akhir dalam kisaran 6-8% dengan nilai akhir a_w = 0,431. Model Midili terpilih sebagai model pengeringan yang sesuai karena menunjukkan nilai R^2 tertinggi = 0,9804 dan nilai SSE dan RMSE yang rendah. Persamaan model Midili adalah MR = 1,000 exp(-0,342*$t^{0,9456}$) + 0,0038*t. Hasil validasi model menunjukkan kesesuaian waktu yang dibutuhkan untuk mengeringkan irisan apel dari kadar air 84,4% basis basah menjadi 6,4% basis basah yaitu 11,5 jam. Waktu yang digunakan lebih efektif sebesar 42,5%, yang menunjukkan kemajuan yang signifikan.*

Kata kunci: irisan apel, pengeringan lapisan tipis, model pengeringan, rasio kelembaban

ABSTRACT

This research was conducted in order to evaluate the drying prosess using the Moisture Ratio (MR) drying model approach among Newton, Page, Henderson-Pabis and Midili. The thin-layer drying experiment was carried out in a Wirastar FDH10 food dehydrator at the constant temperature of 60°C for 23 h. The main responses, i.e, weight loss, moisture content and water activity (a_w) were measured during the process. All data analysis and mathematical modeling was executed with the Microsoft Excel Analysis Tools Solver Add-In. The final weight of the dried apple slices was decreased by 80.2%, and a target moisture content in the range of 6–8% with a final water activity value of a_w = 0.431 was also obtained. Comparing the models, Midili model turned to be the most adequate for describing these data as it presented the highest value of R^2 =0.9804 and low values for SSE and RMSE. The empirical equation for the Midili model was MR = 1.000 exp(-0.342*$t^{0.9456}$) + 0.0038*t. The model was validated which showed a good agreement, and the necessary time to dry from 84.4% on wet basis to 6.4% on wet basis is predicted at 11.5 h. This is a 42.5% increase in the time effectivity, which presents definite progress.

Keywords: apple slices, drying model, moisture ratio, thin layer drying

INTRODUCTION

The food and beverage processing business is continuously expanding in response to modern lifestyle trends, particularly the popularity of consuming food and drinks served directly in restaurants, dining establishments, cafes, and hotels. Beverages such as cocktails, coffee drinks, or mocktails are frequently served, and dried fruits can be utilized as a garnish to provide an elegant appearance, enhance visual appeal, and impart a unique flavour.

Dried fruits, such as dried orange slices, dried pineapple, or dried apple, offer an attractive alternative as a beverage garnish, providing a crisp texture and a more intense flavour compared to fresh fruit. Among these, dried apple slices are the most susceptible product to quality deterioration, exhibiting a faster degradation rate compared to others. This vulnerability stems from the characteristic open pores in dried apple slices, which readily absorb ambient water vapor. Furthermore, according to Ceron *et al*. (2018), dried apples have a high reducing sugar content, resulting in a greater water-holding capacity than other fruits.

Dried fruit is fresh fruit that has been processed by drying to reduce a significant amount of its moisture content. A common approach for modelling the drying of fruit using a dehydrator involves a mathematical framework aimed at predicting moisture content changes over time, known as thin-layer drying kinetics. This model show

*Coressponding Author

how variables such as temperature, time, and fruit type affect the rate of drying. Thin-layer drying is characterized by spreading the material in a thin layer, which facilitates direct and uniform contact with the air used for drying. According to Lahsasni *et al.* (2004), this technique promotes a quicker and more even drying process because hot air consistently extracts moisture from the entire surface area of the material.

The dried apple slices produced by PT Primafood Relasi Utama are created using the thin-layer drying method. Currently, the duration of this drying process depends entirely on reaching the level of dehydration in the product. Such variability in drying times may result in energy inefficiency if it extends beyond what is required. In order to get an efficient drying process that yields a product moisture content meeting SNI 3710:2018 standards (<20%) or aligning with company goals (6−8%), it is essential to assess the drying technique through a modelling approach. Establishing an effective drying model enables the company to identify optimal parameters, including suitable timeframes tailored to the specific attributes of the fruit being dried. Using mathematical models and simulating the drying curve at different operational conditions is necessary to improve process efficiency of a commercial scale drying. Karathanos and Belessiotis (1999) reported, the principle of the model explains how the system operates during the drying process based on various mathematical equations

MATERIALS AND METHODS

Materials and Equipment

The equipment utilized in this research includes a Wirastar FDH-10 food dehydrator, a slicing machine, an a_w meter (water activity meter), an oven, a thermometer, a digital balance, and containers. The materials used in this study were Fuji apples (the average water content and weight were 84.4% and 133.67 grams.) sourced from an imported fruit supplier in Bogor and demineralized water (aquadest).

Methodology

Material Preparation

Fuji apples were stored in a chiller at a temperature of 4−10°C for 24 hours. Storing apples at low temperatures is crucial for slowing the respiration rate and the ripening process, which, in turn, extends the apple's shelf life. Subsequently, the apples were washed using running water. Washing the fruit is a process carried out to clean the fruit, removing dirt, pesticides, microorganisms, and other chemical residues that may adhere to the surface.

The slicing process involved cutting the apples into thin layers with a thickness of 4 mm. The apple slices were then arranged neatly and spread in a single layer on a perforated drying tray, measuring 28×38 cm. Each tray had a capacity of approximately 20 apple slices. The arrangement of the material during the drying process is critical for ensuring the quality of the final product. Uniform distribution of hot air is one of the key factors. The use of perforated trays helps to enhance the airflow around the apple slices, thereby preventing localized over-drying.

Drying Process

The drying process was conducted using a **Wirastar FDH-10 food dehydrator** at a constant temperature of **60°C** for a duration of **23 hours**. The drying machine used is shown in Figure 1.

Figure 1. Food dehydrator Wirastar FDH-10

During the drying process, the following parameters were meticulously monitored and recorded: weight loss (%), moisture content (%), and water activity (a_w). Observations were performed every 30 minutes for the first 7 hours, followed by every 60 minutes for the subsequent 4 hours, then every 120 minutes for the next 4 hours, and finally, every 180 minutes for the remaining 9 hours.

Drying Model Analysis

The drying models employed to describe the drying process of the apple slices are based on the concept of Moisture Ratio (MR). These models include the Newton, Page, Henderson-Pabis, and Midili models. The mathematical equations for these specific drying models are presented in Table 1.

Table 1. Moisture Ratio (MR) Drying Models

No	Drying Model Name	Mathematical Equation
1	Newton	MR = exp(-k*t)
2	Page	MR = exp(-k*t^n)
3	Henderson-Pabis	MR = a exp(-k*t)
4	Midili	MR = a exp(-k*t^n) + b*t

Source : Koloay *et al.* (2017)

The appropriate drying model is selected based on three key statistical parameters: the Coefficient of Determination (R^2), the Sum of Squared Errors (SSE), and the Root Mean Square Error (RMSE). The calculation of these parameters utilizes the following equations:

Coefficient of Determination (R^2)

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pre.i} - MR_{exp.i})^2}{\sum_{i=1}^{N}(\overline{MR}_{pre.i} - MR_{exp.i})^2}$$

Note :

R^2	:	Coefficient of Determination
$\overline{MR}_{pre}$	:	Mean value of predicted moisture ratio
$MR_{pre.i}$	:	Predicted moisture ratio for the i-th observation
MR_{exp}	:	Value of experimental moisture ration
$MR_{exp.i}$	:	Experimental moisture ratio for the i-th observation

Sum Square Error (SSE)

$$SSE = \sum_{i=1}^{N}(MR_{pre.i} - MR_{exp.i})^2$$

Note :

SSE	:	Sum Square Square Error
$MR_{exp.i}$	:	Experimental moisture ratio for the i-th observation
$MR_{pre.i}$	:	Predicted moisture ratio for the i-th observation
N	:	Number of data points/ observations

Root Mean Square Error (RMSE)

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

Note :

RMSE	:	*Root Mean Square Error*
$MR_{exp.i}$	:	Experimental moisture ratio for the i-th observation
$MR_{pre.i}$	:	Predicted moisture ratio for the i-th observation
N	:	Number of data points/ observations

Primary data were obtained from field observations and laboratory testing. Data processing was performed using a quantitative non-linear regression analysis method. This analysis was conducted using the Solver Add-In feature within the Microsoft Excel Analysis Tools software.

RESULTS AND DISCUSSIONS

Drying Process

Fuji apple (*Malus pumila*) is one of the most popular apple varieties globally, distinguished by its characteristic sweetness and crisp texture. The Fuji apple is a hybrid resulting from the cross between the Red Delicious and Ralls Janet varieties (Ku *et al.*, 2016). Its skin typically exhibits a pinkish-red color with slight yellow or green undertones, and its surface is dotted with small specks. The flesh is white to cream-colored and notably juicy. Fuji apples tend to be larger in size compared to other apple varieties.

The production process for dried apple slices involves several stages. The apples sourced from the supplier were initially stored in a chiller at a temperature of 4−10∘C for 24 hours. This storage step was implemented to slow the respiration rate. Subsequently, the apples were washed with running water to remove any dirt and dust accumulated during distribution. After washing, the apples were sliced using a slicing machine to a uniform thickness of 4 mm. According to Li *et al*. (2019), the slice thickness plays a significant role in the final product quality. Slicing was performed carefully to ensure thickness consistency. The sliced product was then arranged neatly and evenly on the perforated drying trays. These trays were subsequently placed inside the Wirastar FDH-10 food dehydrator (Figure 2). The drying process was carried out at a constant temperature of 60∘C for 23 hours. The rate of the drying process was monitored by observing the changes in weight loss (%), moisture content (%), and water activity (a_w) of the apple slices throughout the drying period.

Figure 2. Arrangement of apple slices on trays inside the Wirastar FDH-10 food dehydrator

Weight Loss

Weight loss is defined as the reduction in the total mass of a food material resulting from the removal of water and other volatile components during processing, such as drying, storage, or cooking (Smith and Brown, 2019). As demonstrated in Figure 3, the weight loss of the fruit slices increased proportionally with the duration of the drying time. Drying periods exceeding 600 minutes exhibited a relatively consistent percentage of weight loss for the dried fruit slices, stabilizing at an average of 79.59%. Following a total drying duration of 1380 minutes (23 hours), the apple slices' initial moisture content of 86.13% was reduced to a final moisture content of 5.84%. This corresponded to a total weight loss of 93.22%, with an R^2 value of 0.8997.

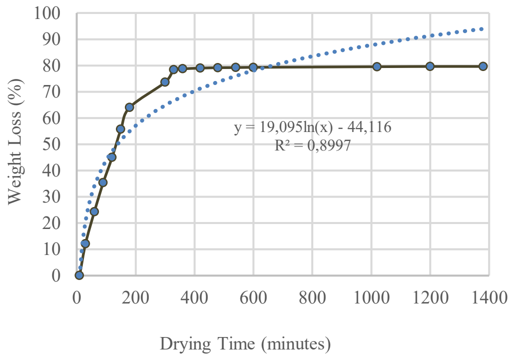


Figure 3. Percentage weight loss of apple slices as a function of drying time

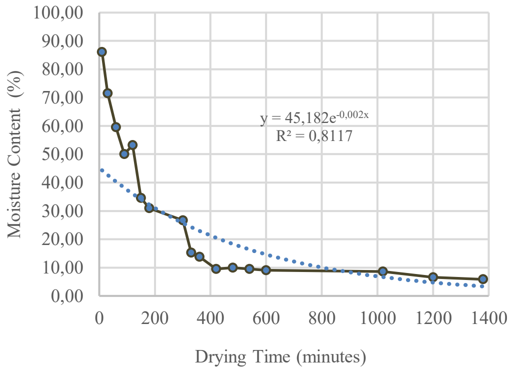
Fuji apples have a relatively high moisture content, which leads to a significant weight loss during drying (Tunde-Akintunde *et al*., 2014). In addition to moisture content, several factors influence the magnitude of weight loss, including temperature, drying time, drying method, and the shape and size of the material. Research by Bakry *et al*. (2021) indicated that higher drying temperatures and longer drying times result in greater weight loss. Drying at high temperatures accelerates water evaporation but may also lead to the degradation of material quality. The duration of drying directly affects the contact time between the heat and the material. A longer heat contact time means a greater amount of water is evaporated.

The drying method also has a significant influence on the weight loss, quality, and final characteristics of food materials. The cabinet drying method on roselle flowers for 7 hours produced dried roselle flowers with the moisture content of 7.5% and the total phenolic compound of 22.43 mg/100 g of material (Purbowati *et al*., 2018). The findings of Doymaz (2017) demonstrated that drying eggplant using different cutting shapes and sizes affected weight loss. Thin slices tend to lose more water and experience greater weight loss compared to thicker cuts. The effect of weight loss on food products during the drying process is highly significant, impacting various aspects such as nutritional quality, sensory attributes, texture, and shelf life.

Moisture Content

Moisture content is a physical property of a material that indicates the amount of water contained within it. It is expected to decrease proportionally with the duration of the drying time. As shown in Figure 4, the moisture content of the apple slices demonstrated a reduction corresponding to the increase in the drying duration.

Figure 4 illustrates that the reduction in the moisture content of the apple slices was quite substantial during the first 300 minutes (5 hours) of drying, dropping by approximately 69-70% and reaching a moisture content of around 26-27%. This rapid initial decrease is attributed to the relatively large mass of free water present on the material's surface. Subsequently, the rate of moisture reduction slows down as the free water on the surface depletes, requiring the evaporation of water bound within the material. This observation aligns with the principle of drying kinetics: once the free surface water is exhausted, the bound water must move via diffusion from the interior to the surface. This bound water then evaporates, facilitated by the drying air flowing around the material.



Fiqure 4. Percentage moisture content of apple slices as a function of drying time

In general, the graph depicting the relationship between drying time and material moisture content typically shows three periods: a period of rapid decrease, a period of gradual decrease, and a period approaching equilibrium (Nurhawa, 2016). The phenomenon observed above illustrates the characteristic trend for drying apple slices, which is a continuous decrease throughout the process. The graph showing the relationship between drying time and material moisture content yielded an R^2 value of 0.8117 (categorized as strong). The R-squared (R^2) value is used to assess the degree to which a specific independent variable influences the dependent variable. There are three common categories for R-squared values: strong (above 0.75), moderate (0.5−0.75), and weak (0.25−0.50) (Hair *et al*., 2011).

Water Activity (a_w)

Water activity (a_w) describes the degree of water availability in a food material, which biologically influences chemical reactions and microorganism growth. The a_w value ranges from 0 (completely dry) to 1 (pure water). Water activity is closely related to the moisture content of the food material. The level of water activity in a food material significantly affects its shelf life (Lahsasni *et al*., 2004).

Water activity (a_w) is a critical factor in controlling microbial growth in food. Microorganisms require a certain level of a_w to survive and proliferate. Rahman and Labuza (2017) stated that the reduction of a_w in food is an effective method for inhibiting the growth of pathogenic microorganisms. Other studies indicate that most pathogenic bacteria can grow at a_w levels above 0.85, while molds and yeasts typically require a_w above 0.80. Water activity also influences the food material's texture and sensory quality.

Figure 5 demonstrates that the water activity (a_w) showed a decreasing trend throughout the drying process. The final a_w value of the dried apple slices was relatively low, specifically 0.431. A low a_w value prevents the growth of most microorganisms such as bacteria, yeasts, and molds, thereby extending the product's shelf life. Products with low a_w tend to be chemically stable because the rates of Maillard reactions and lipid oxidation are reduced. Products with low a_w are typically dry and hard. Conversely, products with high a_w are generally softer but are also at higher risk of becoming soggy or moldy (Rahman and Labuza, 2020).

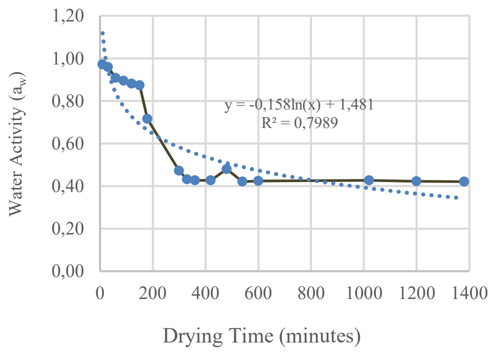


Figure 5. Change in water activity (a_w) of apple slices during the drying process

Drying Model Analysis

The conducted drying process not only demonstrated a decrease in the moisture content of the apples but also showed a corresponding reduction in the Moisture Ratio (MR) value over the duration of the drying period. The Moisture Ratio (MR) is defined as the ratio of the remaining moisture content in the material at a specific time to its initial moisture content. Understanding the pattern of MR reduction is crucial for comprehending and optimizing the drying process of food materials. The rate of decrease in the Moisture Ratio (MR) during the drying process is illustrated in Figure 6.

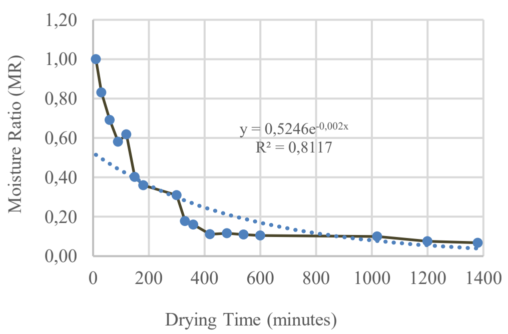


Figure 6. Change in moisture ratio (MR) of apple slices during the drying process

Both Figure 4 and Figure 6 clearly demonstrate a decreasing trend in moisture content and MR value throughout the drying process. The decline pattern of the MR during drying is generally categorized into several phases.

In the initial drying period, MR decreases linearly because the drying rate is relatively constant, primarily due to the evaporation of surface moisture. Research by Mujumdar (2006) indicates that this phase is characterized by the rapid evaporation of easily removed surface moisture. The second phase is often fluctuating, which can be caused by various external and internal factors that influence the drying rate. This fluctuating phase reflects temporary, non-monotonous changes in the drying rate. Once the free water on the material surface is depleted, the drying process enters a phase with a slower rate of decrease. In this phase, bound water from the internal core of the material moves to the surface via diffusion, causing the drying rate to slow down, and the MR to decline more slowly, following a negative exponential curve. Khalloufi and Ratti (2003) noted that internal diffusion and resistance to mass transfer become the primary limiting factors during this period.

Drying models are essential tools for detecting the moisture ratio behavior of materials during the drying process. Mathematical drying models are capable of significantly explaining the parameters that impact the drying process, including the drying conditions, the type of dryer used, and the characteristics of the material being dried (Onwude *et al.*, 2016). The plot comparing the Moisture Ratio (MR) of the apple slices with the Newton, Page, Henderson-Pabis, and Midili models is presented in Figure 7.

The Moisture Ratio (MR) drying model analysis was performed using a quantitative non-linear regression analysis method implemented via the Solver Add-In feature of Microsoft Excel Analysis Tools software. This analysis yielded the model constants, Coefficient of Determination (R^2), Sum of Squared Errors (SSE), and Root Mean Square Error (RMSE). The MR drying model constants, identified as k, n, a, and b, were utilized to generate the predicted MR values through the non-linear regression analysis.

The level of fit for the Moisture Ratio (MR) drying models can be assessed by analyzing the R^2, SSE, and RMSE values for each model. The R^2 analysis is a statistical test that describes how well the model variance matches the observed data set, or represents the difference between the observed and expected values within the model. R^2 values range between 0 and 1, where a value of 0 indicates that the model explains no observed variation, and a value of 1 indicates the model perfectly explains the observed variation.

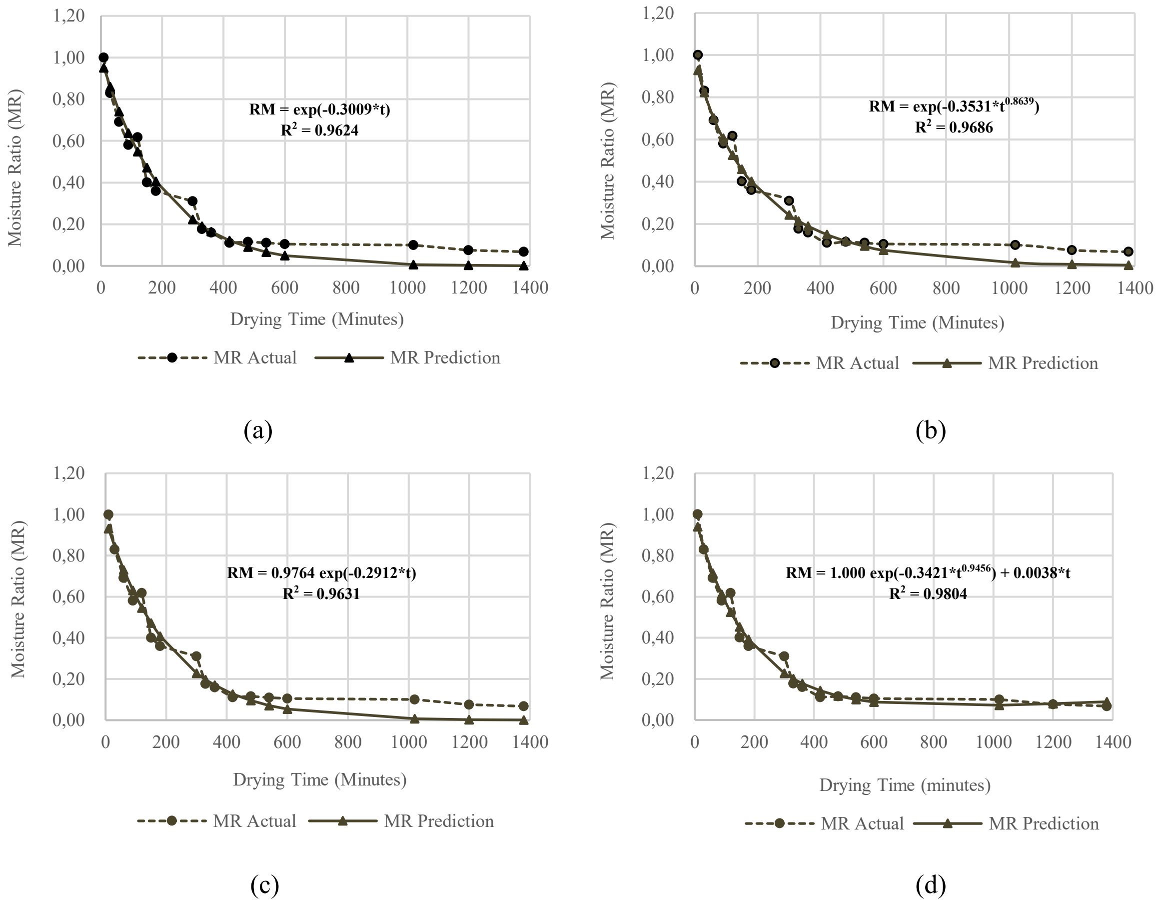


Figure 7. Drying model graphs for apple slices: (a) Newton, (b) Page, (c) Henderson-Pabis, and (d) Midili

Table 2. Constants, R^2, SSE, and RMSE Values for the MR Drying Models

Drying Model	Drying Model Constants				R^2	SSE	RMSE
	k	n	a	b			
Newton	0.3009				0.9624	0.0530	0.0558
Page	0.3531	0.8639			0.9686	0.0443	0.0510
Henderson-Pabis	0.2912		0.9764		0.9631	0.0520	0.0553
Midili	0.3421	0.9456	1.0000	0.0038	0.9804	0.0277	0.0404

SSE analysis is a statistical test used to measure the total difference between the actual and predicted values; an SSE value approaching zero signifies a better fit for the observed model. RMSE analysis is a measure of the error level based on the difference between two corresponding variables; a smaller RMSE value indicates a greater predictive accuracy for the model. The constants, R^2, SSE, and RMSE values resulting from the MR drying model analysis are presented in Table 2.

The modelling results and non-linear regression analysis of the Moisture Ratio (MR) drying models indicated that the Midili model exhibited the highest R^2 value (0.9804) and the lowest SSE and RMSE values (0.0277 and 0.0404, respectively) compared to the other models tested. This outcome strongly suggests that the Midili model is the most appropriate and best-fitting model. Subsequently, a precision test was performed by comparing the predicted MR values generated by the Midili model with the experimental MR values (actual MR) obtained from the study. The relationship between the actual MR and the predicted MR is presented in Figure 8.

Figure 8 shows that the curve angle formed between the actual MR and the predicted MR closely approaches a 45∘ angle, indicating a strong agreement between the predicted and experimental MR values (Prasetyo *et al*., 2018). Furthermore, the graph illustrating the relationship between the actual MR and the predicted MR also displays a very high R^2 value (0.9807), which is close to 1 and falls into the strong category. The analysis results from the drying model and the level of fit detailed in Table 2 and Figure 8 unequivocally demonstrate that the mathematical equation of the Midili model is highly suitable. This confirms that the most appropriate

Moisture Ratio (MR) drying model for dried apple slices is the Midili model.

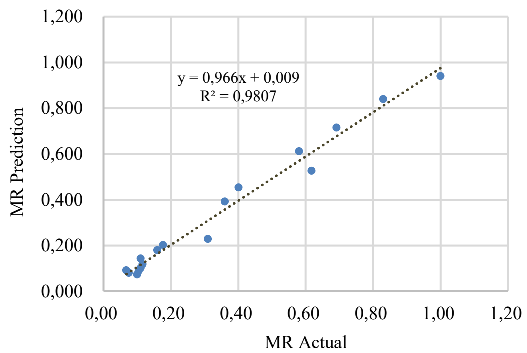


Figure 8. Relationship between experimental MR (Actual MR) and predicted MR using the Midili Model

Model Validation

The drying model validation was performed quantitatively. The model validated was the Midili Moisture Ratio (MR) model. Validation involved conducting a re-drying experiment based on the drying time generated by the modeling. The validation is considered successful if the final moisture content adheres to SNI 3710:2018 (<20%) and meets the company's requirement for a final moisture content in the range of 6−8%.

The validation target was an MR final value of 0.081, which converts to a moisture content of 7%, and a water activity (a_w) value of <0.6, with a total drying duration of 690 minutes (11.5 hours). The validation test yielded a final MR value of 0.074, converting to a moisture content of 6.4%. This result shows a difference of 0.6% from the target. This discrepancy is most likely due to the frequent opening of the food dehydrator lid during sampling, which alters the environmental conditions around the sample. This aligns with the findings of Kingsly *et al*. (2007), who stated that environmental conditions such as temperature, humidity, and air circulation have a major impact on drying efficiency and effectiveness. Differences in these conditions between the experiment and the model can cause significant variations in the results, emphasizing the importance of carefully controlling and reproducing these conditions to minimize such differences. Additionally, a final a_w value of 0.431 was obtained. This value is below the safe limit, making the product safe for consumption.

The study demonstrates that the Midili Moisture Ratio (MR) drying model resulted in a significantly shorter drying time than previously used. The prior drying time was 20 hours, whereas the modeled time was reduced to 11.5 hours. This result shows that using the Midili model can achieve a 42.5% reduction in drying time. According to Li *et al*. (2019), reducing the drying time can increase production efficiency by accelerating the production cycle, decreasing energy consumption, and reducing electricity costs. Drying for 20 hours previously required an energy cost of Rp 28,894, while drying for 11.5 hours requires an energy cost of Rp 16614. Utilizing the drying time derived from the model saves Rp 12280 per drying batch. This study confirms that the shorter drying time contributes to reducing the total operational time and expediting product delivery to customers.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

During the drying of apple slices, a notable decline in the drying rate was recorded, as indicated by measurements of weight loss, moisture content, and a_w values. The final weight of the apple slices exhibited a shrinkage of 93.22% from their original weight, while the final moisture content fell within the range of 6−8%, and the final a_w value measured at 0.431. The chosen Moisture Ratio (MR) drying model is identified as the Midili model, represented by the equation: $MR = 1.000 \exp(-0.342 * t^{0.9456}) + 0.0038*t$, with an R^2 value of 0.9804. This model displayed both the highest R^2 value and the lowest SSE and RMSE values, which were nearly zero. The Midili model effectively established a correlation where the predicted moisture ratio aligned closely with the actual observed moisture ratio, achieving an R^2 value of 0.9807. According to this model, the optimal drying period is determined to be 11.5 hours, culminating in a final moisture content of 6.4%. This duration signifies an efficiency improvement of 8.5 hours, equating to a 42.5% reduction in overall drying time.

Recommendations

Suggestions, further application of the MR Milidi drying model in industry can be used to predict product drying times by knowing the initial and final moisture content of the target product.

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