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Investigating drying kinetics of cassava chips under continuous and intermittent drying operation

Raden Faridz[1] and Raden Arief Firmasyah[1,*]

[1]Department of Agroindustrial Technology, University of Trunojoyo, Bangkalan, Indonesia
[*]Corresponding author: arief.firmansyah@trunojoyo.ac.id

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Abstract

Krepek tette is one of the popular cassava chips, which has become a signature snack from Pamekasan, Indonesia. Several studies have shown that its production process is significantly different from other chips, leading to distinct tastes and textures. One critical step in the process is drying, which largely depends on the open sun drying method. This method has been reported to produce better product quality but causes contamination and consumes more energy. To overcome the challenges, intermittent drying has been introduced as a novel technology that maintains product quality and consumes less energy. Therefore, this study aimed to determine drying kinetics of *K. tette* based on the thin layer drying model using 2 different methods, continuous and intermittent. Experiments were conducted with continuous and intermittent drying with an oven dryer at 50°C and 60°C. Intermittent drying was conducted by leaving the product out of the oven and placing it in a desiccator. The duration was 10 and 20 min, while the resting time was 20 and 40 min, respectively. The result showed that drying kinetics of *K. tette* provided a good fitting curve model based on the Midilli and Kucuk model for continuous and intermittent methods. In addition, intermittent drying at a resting time of 10 min provided a shorter effective drying time of 34% compared to the continuous method. The intermittent drying condition also had lower effective moisture diffusivity. These results confirmed that intermittent drying reduced energy consumption by shortening the effective drying time.

Keywords: Cassava, Convective drying, Intermittent drying, Drying models, Energy-saving

Nomenclature			
a, b, k	coefficient of drying model	M_{t+dt}	moisture content at $t + dt$
DR	drying rate (g water/g solid) min^{-1}	M_t	moisture content at t
D_{eff}	effective moisture diffusivity, m^2/S	$MR_{pre,t}$	the i^{th} predicted moisture ratio by model
k_{slope}	estimated slope of straight line of equation 4	$MR_{exp,t}$	the i^{th} experimental moisture ratio
L	thickness, m	N	Number of observations
MR	Dimensionless Moisture Ratio	n	Number of constants in the model
M	Moisture content of krepek (% d.b)	t	time, s
M_i	Initial moisture content (% d.b)	χ^2	reduced chi-square
M_e	equilibrium moisture content (% d.b)		

1. Introduction

Cassava is a major part of Indonesia's cuisine which is widely used as the main ingredient for the production of various snacks, including *thiwul*, *gethuk, lemet, tape,* and chips. Among these snacks, chips have been reported to be the most consumed due to their taste, cooking procedure, and ability to complement other foods. In

Pamekasan, cassava is often processed differently into chips by steaming, flattening, dying, and frying, rather than the conventional method of slicing and frying after peeling [1]. This different process gives the product a different taste and texture as well as a different name, *Krepek tette*.

Although *K. tette* has a potential market in Indonesia, its quality largely varies because the production process still relies on microenterprises. Several studies have shown that microenterprises are known for the use of traditional/manual processes, aged machines, or manual, and market orientation is mostly local [2]. One of the essential steps in the production of *K. tette* is drying, which is often conducted using open sun drying. However, this method has a high potential for contamination, proves difficult in controlling the parameters [3,4], and cannot be applied everywhere at any time.

Drying is a preservation method comprising the use of heat and mass transfer mechanisms, which can lead to changes in the nutritional quality, color, flavor, and texture of the product. Moreover, the use of heat has a significant correlation with higher energy consumption. According to previous studies, there are 2 types of drying methods, namely continuous and intermittent. These methods have different durations of heat exposure, where continuous drying (CD) exposes the product during the process, while intermittent drying (ID) only exposes periodically [5]. Several studies have shown that ID has more benefits than CD [6–9], such as reduced drying time [5,9], energy consumption [10], and improved quality of dried material [11–13]. Mathematical modeling is often used to determine the moisture content of the product during the drying process to obtain the most appropriate condition [8] and to describe drying kinetics, which is essential for determining quality. The thin-layer drying model is the most widely used and is categorized as theoretical, semi-theoretical, and experimental [14].

In line with these findings, several studies have modeled drying kinetics of cassava chips [15–18], but none has focused on the use of ID, particularly in Indonesia. Therefore, this study aimed to obtain drying kinetics of *K. tette* based on the thin layer drying model using 2 different methods, continuous and intermittent.

2. Materials and methods

2.1 Material

This study was carried out from October until November 2022 in the laboratory of agro-industrial product quality analysis (University of Trunojoyo Madura, Bangkalan). *Krepek tette* was made from cassava obtained from the fresh market at Kamal, Bangkalan. The cassava was washed, peeled, and steamed, then the steamed cassava was flattened with a thickness of 0.83 ± 0.01 mm. Each sample weighed 3 ± 0.001 g and was placed on the aluminum tray, which was produced by imitating the recipe from the *K. tette* enterprise at Pamekasan.

2.2 Experimental procedures

The drying experiment was conducted using an oven dryer (UNB 400, Memmert GmbH, Schwabach. Germany). The temperature was designed for 50 ± 0.1°C and 60 ± 0.1°C for all conditions (continuous and intermittent). In the intermittent procedure, resting times were used for 10 min (R10) and 20 min (R20), and all conditions were performed in triplicate. Before the drying experiment, cassava-steamed and dried chips from enterprise were dried in the oven at 105°C for 6 h to estimate initial and final moisture content. The moisture of these products was shown in Table 1, and the morphology of the chips in Figure 1. The content of cassava-steamed was used as the initial moisture content (M_i) and that of dried chips was used as the equilibrium moisture content (M_e) to determine the ratio.

Table 1 Initial and final moisture content of samples taken from *Krepek tette* enterprise.

	Initial moisture content					Final moisture content				
Sample number	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5
Moisture Content (w.b)	54.4%	56.4%	57.7%	56.8%	55.5%	9.7%	9.8%	10.2%	9.6%	9.9%
Average moisture content (w.b)	56%					10%				
The standard deviation of moisture content (w.b)	0.011598					0.001953				
Coefficient variation of moisture content (Standard deviation/Average)	0.020652					0.019872				

The experimental procedure for ID was followed by Pereira et al. [9] with modification, and 3 trays were required namely tray 1 which was placed in the dryer, and the remaining sample remained outside the oven. After the resting period, tray 2 was placed in the dryer, the first one was moved to the desiccator without silica, and tray 3 remained outside the dryer and desiccator. Subsequently, After the resting time was over, tray 3 was placed in the dryer, and tray 1 was moved to desiccator 2 respectively. The cycle ended when the moisture content reached about 10% (w.b). Contrarily, all trays were placed and taken simultaneously for CD until the moisture content reached about 10% (w.b). Mass measurements were periodically performed in all experiments at 10, 30, and 60 min.

(A) (B)

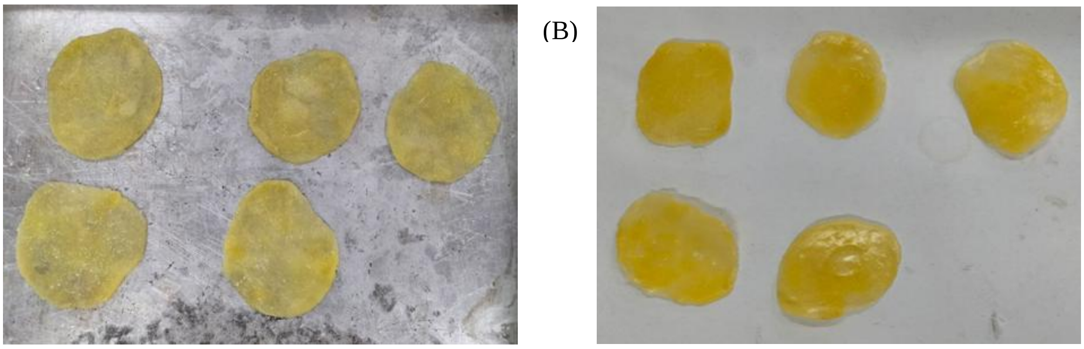

Figure 1 Morphology of chips before drying (A) and after drying (B).

2.3 Mathematical modeling

This study used 8 thin layer models presented in Table 2 to simulate the drying kinetics of the *K. tette*. Equations (1) and (2) showed the moisture ratio and drying rate calculation.

$$MR = \frac{M - M_e}{M_i - M_e} \tag{1}$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{2}$$

Table 2 Thin layer mathematical models.

No	Model Name	Equation	Reference(s)
1	Henderson and Pabis	$MR = a\ exp(-bt)$	[14]
2	Lewis	$MR = exp\ bt$	[19]
3	Page	$MR = exp(-at^b)$	[20]
4	Peleg	$MR = 1 - t/(a + bt)$	[9]
5	Silva et alii	$MR = exp(-at - bt^{1/2})$	[21]
6	Wang and Singh	$MR = 1 + at + bt^2$	[8]
7	Midilli and Kucuk	$MR = a\ exp(-bt^n) + kt$	[5]
8	Logarithmic	$MR = a\ exp(-bt) + k$	[22]

The MR and drying time curve were fitted with all thin-layer mathematical models in Table 2. SOLVER in Microsoft Excel (2016) was used to perform regression analysis. Non-linear regression was performed to evaluate the best fit of the thin layer model based on the correlation of determination (R^2) and reduced chi-square (χ^2). The nearest value of R^2 to 1 and the value of χ^2 was lower than 0.005, which was the criteria for the selection model. The reduced chi-square was calculated as equation (3).

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{pre,t} - MR_{exp,t}\right)^2}{N - n} \tag{3}$$

The effective moisture diffusivity coefficients during the drying of the thin layer were calculated at different temperatures and experiments. The calculation was based on Fick's second law of moisture diffusion and was expressed by equation (4) for the thin slab model.

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

The effective moisture diffusivity was calculated by plotting in MR and drying time, the slope of the graph (k_{slope}) was used to determine D_{eff} as:

$$k_{slope} = \frac{\pi^2 D_{eff}}{4L^2} \tag{5}$$

Equation (5) was also used to determine D_{eff} at ID, although this equation was frequently used in CD. This was performed well when comparing CD and ID by Mishra et al. [23] who compared CD and ID utilization for potatoes.

3. Results and discussion

3.1 Mathematical Models for Fitting Drying Curves

All drying kinetics models were applied in every experiment, and all parameters of the proposed model and the result of statistical analysis were presented in Table 3. Based on the statistical result, R^2 had more than 0.9 which indicated that all models agreed to represent the drying kinetics of the product. Moreover, to obtain the best model for all experiments, the selection was based on criteria of the highest R^2 and the least χ^2. For continuous (resting time = 0) experiments at drying conditions at 50°C, Page, Midilli, and Kucuk models showed a good fitting model. These authors produced a good-fitting model at a drying condition of 60°C, and for the intermittent experiment, more than 2 succeeded in representing the drying kinetics of *K. tette*. At drying conditions of 50°C and resting time of 10 min, Page, Silva et alii, and Midilli and Kucuk representatives were the best-fitted models to describe experimental data.

Silva et alii and Middli and Kucuk model were the best fit at a resting time of 20 min. A total of 3 mathematical models, namely Midilli and Kucuk, Silva et alii, and Wang and Singh, fitted to the experimental data at a drying condition of 60°C and resting time of 10 min. In the same temperature condition and resting time of 20 min, only the Midilli and Kucuk models were best fitted. In the overall experiment, these models were the best-fitted models to represent the drying kinetics of the *K. tette*. Moreover, for validation, plotting between the experimental values was shown in Figure 1, and it showed good agreement between experimental and predicted values.

Midilli and Kucuk's presented the best-fit models to express the thin-layer drying kinetics of *K. tette* in CD and ID. These results were analogous to several authors who also reported the accomplishment of this model for CD of dill and parsley leaves [23], rough rice grain [24], onion [8], and spring leaves [14]. In ID, these results were a good agreement, which reported that the patterns were the best for the drying characteristics of soybean [5] and Camellia oleifera seeds [25]. These results proved that the models reasonably depicted moisture changes in food products during drying [26]. In addition, the results were also supported by the physical properties of *K. tette*, which had low porosity and density, and the materials dominated diffusion in transfer phenomena [25]. This was relevant because these models were modified from Fick's second law of diffusion [26].

Table 3 Coefficients of thin layer mathematical model.

Resting time (min)	Temp (°C)	No. Model	Coefficients	R^2	χ^2	No. Model	Coefficients	R^2	χ^2
0	50	1	a = 1.09878	0.98253	0.00282	6	a = -0.00944	0.99270	0.00175
			b = 0.01378				b = 0.00002		
		2	b = 0.01248	0.98638	0.00501	**7**	**a = 0.9981255**	**0.99847**	**0.00032**
		3	a = 0.00208	0.99819	0.00040		**b = 0.001751**		
			b = 1.40657				**n = 1.45131**		
		4	a = 84.62308	0.97748	0.00500		**k = 9.36E-05**		
			b = 0.58397			8	a = 1.1797152	0.98782	0.00213
		5	a = 0.01939	0.99556	0.00063		b = 0.011142		
			b = -0.05990				k = -0.10608		
0	60	1	a = 1.10227	0.94787	0.01218	6	a = -0.01226	0.99453	0.00170
			b = 0.02154				b = 0.00001		
		2	b = 0.01941	0.95795	0.01584	**7**	**a = 0.9948496**	**0.99890**	**0.00023**
		3	a = 0.00118	0.99595	0.00078		**b = 0.001871**		
			b = 1.71344				**n = 1.529983**		
		4	a = 81.84761	0.99430	0.00139		**k = -0.00143**		
			b = 0.09207			8	a = 3.3267265	0.99495	0.00135
		5	a = 0.03470	0.98022	0.00379		b = 0.004083		
			b = -0.10349				k = -2.296		

Resting time (min)	Temp (°C)	No. Model	Coefficients	R^2	χ^2	No. Model	Coefficients	R^2	χ^2
10	50	1	a =1.063332048	0.98700	0.00210	6	a = -0.015360179	0.98863	0.00298
			b = 0.020826				b = 6.27E-05		
		2	b = 0.019462313	0.98952	0.00309	**7**	**a = 1.004389096**	**0.99912**	**0.00019**
		3	a = 0.005894407	0.99859	0.00031		**b =0.005148**		
			b = 1.303994				**n = 1.352886**		
		4	a = 55.67904213	0.98740	0.00247		**k = 0.000263**		
			b = 0.549075			8	a = 1.174611976	0.99207	0.00139
		5	a = 0.028557947	0.99795	0.00027		b = 0.016243		
			b = -0.06192				k = -0.13337		
10	60	1	a= 1.066305	0.98432	0.00267	6	a =-0.01874	0.99331	0.00176
			b = 0.025037				b = 9.49E-05		
		2	b = 0.023364	0.98531	0.00382	**7**	**a =1.005074**	**0.99951**	**0.00008**
		3	a = 0.007641	0.99457	0.00122		**b =0.00477**		
			b = 1.298015				**n =1.459639**		
		4	a=42.8288	0.97611	0.00534		**k =0.000727**		
			b=0.626404			8	a =1.105283	0.98903	0.00186
		5	a =0.035873	0.99747	0.00071		b =0.022658		
			b =-0.07778				k =-0.04828		
20	50	1	a =1.033403382	0.99338	0.00121	6	a =-0.010285185	0.99732	0.00044
			b =0.012797				b =2.99E-05		
		2	b =0.012303264	0.99361	0.00162	**7**	**a = 1.001504282**	**0.99977**	**0.00004**
		3	a =0.006534635	0.99648	0.00067		**b =0.003862**		
			b =1.146227				**n =1.29938**		
		4	a =78.63162187	0.98881	0.00177		**k =0.000451**		
			b =0.645124			8	a =1.054879852	0.99362	0.00116
		5	a =0.015994159	0.99802	0.00039		b =0.012146		
			b =-0.03069				k =-0.0257		
20	60	1	a =1.0306	0.98834	0.00191	6	a =-0.01415	0.99335	0.00164
			b =0.016412				b =5.98E-05		
		2	b =0.015867	0.98834	0.00221	**7**	**a =0.999197**	**0.99994**	**0.00001**
		3	a =0.008236	0.99222	0.00133		**b =0.00364**		
			b =1.159123				**n =1.40626**		
		4	a =59.67782	0.98163	0.00316		**k =0.000819**		
			b =0.663687			8	a =1.037095	0.98837	0.00190
		5	a =0.021246	0.99432	0.00100		b =0.016155		
			b =-0.04047				k =-0.00761		

3.2 Drying kinetics

Figure 2 presented the drying kinetics for CD and ID, and effective drying time was used to depict the drying kinetics of ID rather than the total drying time to compare the drying kinetics between these kinetics. Effective drying time was determined when the product remained inside the dryer, and because of this, ID was called a pseudo-CD process [9]. The total drying time of CD at 50°C to reach moisture equilibrium was 240 min, and that of 60°C was close to 90 min. In addition, that of 10 min and temperature conditions of 50°C and 60°C, respectively, were 340 min and 310 min. Simultaneously, the total drying time at a resting time of 20 min was longer, 500 min and 380 min for temperatures 50°C and 60°C, respectively. These results showed that higher temperatures affected a reduction of drying time, and raising the temperature by 10°C reduced approximately 60% of drying time at CD. The ID was reduced by 8.8% and 24% for resting time, 10 min and 20 min, respectively. This phenomenon confirmed that drying time was inversely proportional to air temperature increment, as reported by several authors [14,23,27]. The relationship between air temperature and drying time happened due to an increase in the product's thermal gradient. An increase in the rate of mass transfer of water [29,30], was comparable to results from different studies on drying of various food and non-food products [28–31]. However, the use of higher temperatures to shorten drying time provided drawbacks to the qualitative properties of the product and required high specific energy consumption [32]. These were typical of the hot-air drying method, which was dominant in convective heat transfer [33].

The drying rate for all experiments decreased along with moisture content, as presented in Figure 3. All experiments demonstrated a falling rate period, except ID at a resting time of 10 min and a temperature of 50°C. This showed a constant drying period ranging from approximately 90% to almost 60%. Moreover, the slope at CD was gentler than both intermittent dryings.

All drying conditions encountered a falling-rate period for both ID and CD, and it happened that the ratio of the surface area to the volume of the *K. tette* was sizable. However, the decrease of moisture content was higher than in the center at the initiation of the drying period [5], and it also proved that internal moisture diffusion dominated [19], particularly in CD which affected ID obliquely through resting time. During this period, internal moisture diffused to the surface area of the product due to the lack of driving force created by the air temperature. Subsequently, when a form of activeness was applied, moisture removal increased as well as the drying rate [7,34].

Based on Figure 4 drying kinetics was described by the established model, Midilli and Kucuk. This was limited to effective drying time at 160 min and 90 min to compare fairly between CD and ID about effective time-saving. The criteria to determine the limit of this function was an experiment that reached MR value at 0.10 first. Observation of drying kinetics from Figure 4 showed significant differences between ID and CD at the same temperature study, which was shown by the value of MR dropping more in ID than CD at the same periodic time. The result was linear, with Pereira et al. [9] observing that rice grain lost more moisture in ID than in the CD. For instance, at 50°C, the time required to reach MR 0.20 for CD, ID (R10), and ID (R20) was 113min, 74min, and 120min, respectively. ID at a resting time of 10 min reduced drying time to 34% lower than CD. However, the increase in resting time did not shorten the effective drying time. A similar result was obtained at 60°C. The ID (R10) had a less effective drying time than the continuous, about 13% lower, and to reach a similar MR at 0.20, CD took 69 min.

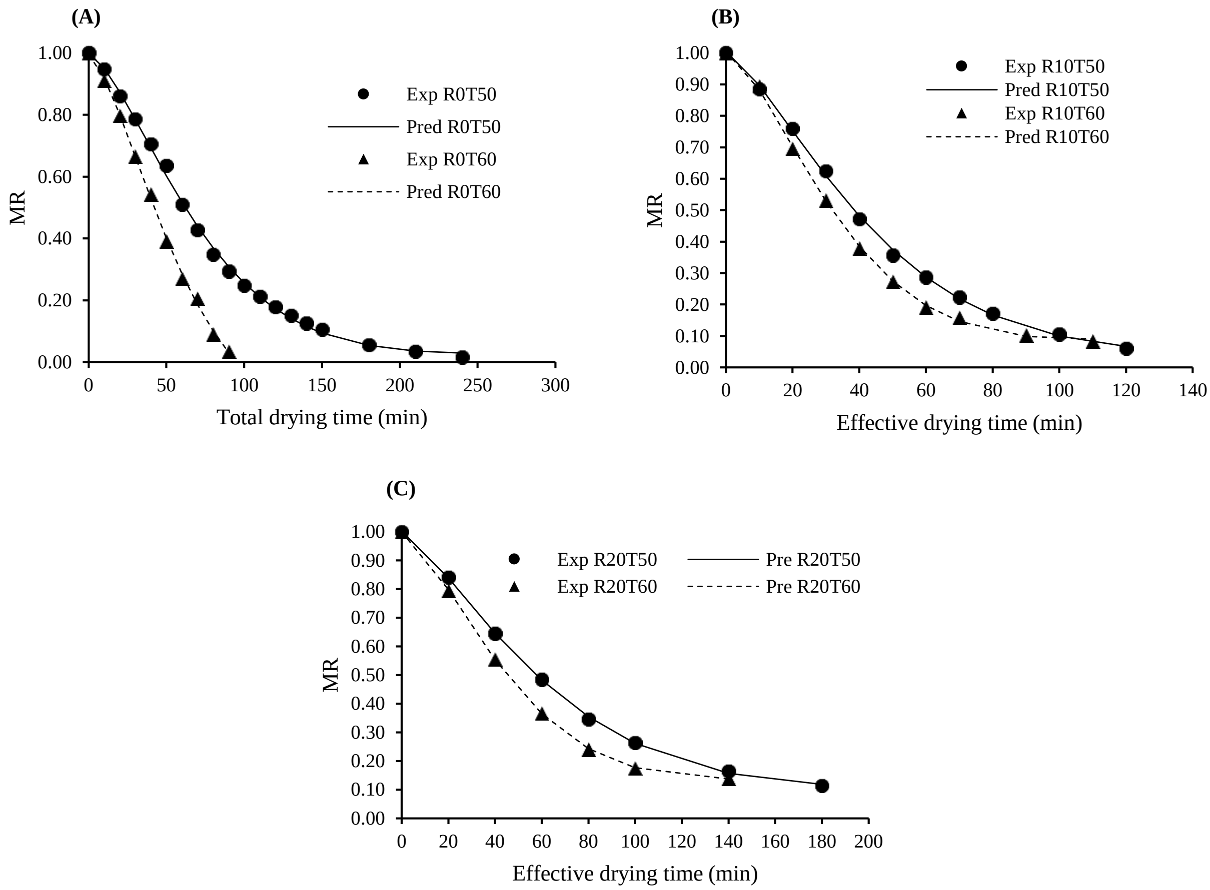

Figure 2 Comparison of experimental and predicted moisture ratio for continuous drying (A), intermittent drying with resting time 10min (B), and resting time 20 min (C).

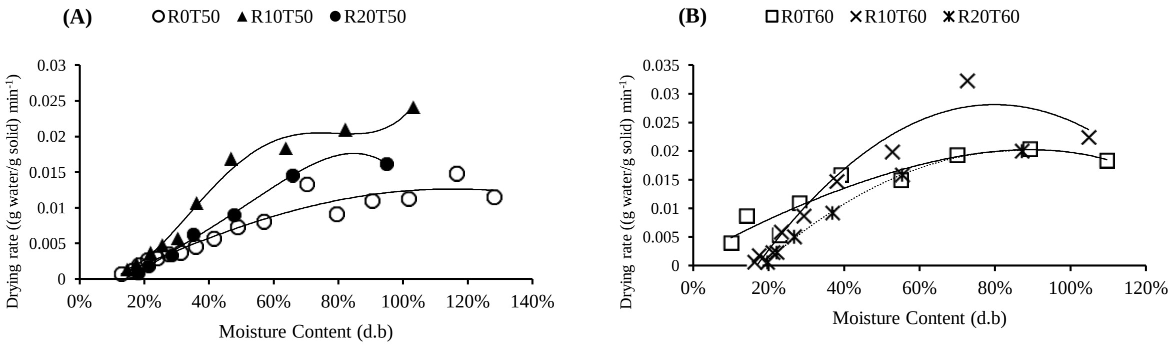

Figure 3 Drying rate as a function of moisture content at different drying conditions (A) 50°C, (B) 60°C.

ID at a resting time of 10 min and 20 min accomplished 60 and 90 min. Figure 4(b) showed a thoughtful result of the CD experiment, and when the effective drying time was over 70 min, the MR value declined steeper than ID at resting times of 10 min and 20 min. This result was confirmed by Figure 3(b), that the drying rate of CD tended to exceed equilibrium moisture content ($M_e = 10\%$) which led to the exclusion of the experiment 60°C from further discussion.

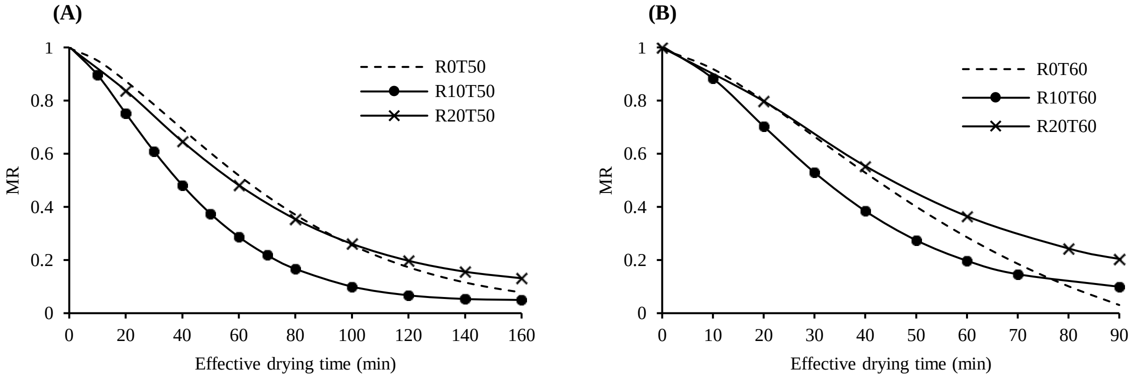

Figure 4 Comparison of continuous and intermittent drying described by the Midilli and Kucuk model at temperatures of 50°C (A) and 60°C (B).

As a result of the comparison between CD and ID, the experiment at 50°C showed that ID at a resting time of 10 min had more effective time-saving than CD and, consequently, affected lower energy consumption for drying. This confirmed similar reports from the different authors, which also reported the effective drying time of soybean [5], *Ganoderma tsugae* Murril [7], and rough rice [9] which were shorter at ID. When the product favored a period of no heating, moisture content depleted. Subsequently, when the heating process resumed, the moisture removal rate increased [35]. Franco et al. [12] explained that ID enabled control of the surface temperature of the product, which led to less damage, such as cracking and fissure [9].

ID also presented high thermal efficiency compared to CD by reducing energy utilization during drying [7]. This efficiency was attained when the drying rate was lower and vice versa [36]. In addition, the result showed that prolonged resting time did not significantly shorten effective drying time. The results supported by different studies allowed a longer resting time that caused a reduction [7,19,37]. In addition, to enhance the benefit of ID, understanding heat and mass transfer during the drying process, and the properties of the product was crucial to selecting an appropriate resting time [38].

The principle of ID was controlling the supply of thermal energy, and it could be achieved by varying the air rate, temperature, humidity, or operating pressure [38]. Kumar et al. [38] classified ID into 4 categories, first, the combined drying method, meaning convective and microwave drying [26,32,39,40]. Second, different tempering periods were used [9,19,25]. Third, different temperature drying methods [8,10] and varying drying air conditions [7] were used. Moreover, this study was classified as ID by varying tempering periods, and all this showed that it produced better quality and reduced energy consumption than CD.

3.3 Effective moisture diffusivity

Effective moisture diffusivity (D_{eff}) values at different temperatures and resting times were presented in Table 4. Significant differences existed in D_{eff} value between CD and ID for both temperature experiments, and the D_{eff} for CD was higher than ID at all temperatures. In addition, the resting time of 10 min had a higher value than the resting time of 20 min for all temperature conditions. This resulted in the higher value of D_{eff} causing the extended period of resting time to result in lower D_{eff} value.

Table 4 Effective moisture diffusivity of *Krepek tette* at different conditions.

Temp (°C)	Resting time (min)	D_{eff} (m^2/s)	Temp (°C)	Resting time (min)	D_{eff} (m^2/s)
50	0	$1.56\ x10^{-8}$	60	0	$2.56\ x10^{-8}$
	10	$1.94\ x10^{-10}$		10	$2.17\ x10^{-10}$
	20	$6.43\ x10^{-11}$		20	$8.75\ x10^{-11}$

The D_{eff} value shown in Table 3 indicated that it was within the standard value for food materials between 10^{-12} and 10^{-8} m^2/s [41]. These results showed that it strongly depended on drying temperature and supported the different studies [14,19]. Moreover, the D_{eff} value of CD was higher than ID for all treatments, and a lower prolonged resting time was performed. These contradicted Park et al. [5] and Pereira et al. [9], that the value of ID was greater than CD, and longer resting time performed a greater D_{eff} value. During a resting time, the surface layer favored decreasing temperature, and lower temperature performed the lower activity of water molecules [42]. Consequently, the moisture content changed to tiny and D_{eff} became low. These phenomena implied that rather than temperature, moisture content had a significant effect on diffusivity [43].

4. Conclusion

In conclusion, the Midilli and Kucuk models performed the best fitting thin layer drying kinetics model for CD and ID. The result showed that ID provided a shorter effective drying time than CD and, consequently, more effective time-saving. However, a prolonged resting time did not shorten the effective drying time, knowing about the drying process and properties of the product was recommended to obtain the maximum benefit of ID. The result showed that a resting time of 10 min provided the best condition to attain the benefit of ID while drying off *krepek tette,* and was formulated by the Midilli and Kucuk model as $MR_{T=50} = 1.004\ exp(-0.0051t^{1.352}) + 0.00026t$.

5. Acknowledgements

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