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https://doi.org/10.5109/5909081

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 8, pp.134-140, 2022-10-20. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University
バージョン：

Mathematical Modelling and Thin Layer Drying of Sago Starch using Infrared Dryer

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Abstract: *The drying of sago starch was investigated using an infrared dryer. The effect of the temperature on the drying rate of the samples at various temperatures (70°C,80°C, and 90°C) was studied. The drying time decreased with an increase in drying temperatures. There is an absence of a constant rate from the drying curve, and sago drying occurs in a falling rate period. Five thin layer drying models were fitted to the drying data. The performance of these models was investigated by comparing the determination of coefficient (R^2), chi square (X^2) and Root Mean Square Error (RMSE) between the observed and predicted moisture ratio. Among all the models, Midilli-kucuk model gave the best results with 99% accuracy. This result concludes that Midilli-kucuk model can adequately describe the drying behavior of sago starch under infrared drying.*

Keywords: Drying kinetics; Infrared; Mathematical modelling; Sago starch; Thin layer drying

1. INTRODUCTION

Sago starch is derived from the spongy center, or pith, of different tropical palm stems, particularly Metroxylon sagu. According to [1], sago starch is considered the main staple for the rural citizens of New Guinea and the Moluccas, where it is known as sakskak, rabia, and sagu in their native languages. The trunk of the sago palm has been used to obtain starch as a staple food for human consumption or fed to livestock [2].

In the Southeast Asian regions, sago starch has become a basic foodstuff. It has been widely known as the "staff of life" in Indonesia since it was the primary source of carbohydrates for humans before rice was invented. According to [3], the demand for sago is expected to rise as sago starch becomes an essential raw ingredient in the food sector. In terms of yield and pricing, sago starch has a competitive edge in the market.

The sago palm is the most adaptable cash-crop-starch producer, with a wide range of applications. Food ingredients, high fructose syrup, glucose, and the edible film "lemantak" are just a few of the uses for native sago starch [4-6]. On the other hand, modified sago starch is widely utilized in several applications, such as ice packs and aroma gels as an absorbent starch gel [6]. With the help of biotechnology advancements, sago starch can be converted into high-value products such as ethanol for fuel, acetic acid, and lactic acid, all of which have high market value in the biopolymer industry [4-5, 7].

In the food industry, drying is a critical step. The starch is dried in modern sago processing factories to extend its shelf life, save packaging costs, and improve its appearance. However, a study conducted by [8] showed that several contemporary sago processing processes have altered the characteristics of the sago starch. Tray drying, drum drying, fluidized bed drying, flash drying, microwave-vacuum, or infrared (IR) drying are all examples of drying methods used in starch or flour production. Heat can be appended from an outside object through conduction, convection, and radiation or derived within solid objects through electric resistance [9]. With identical circumstances, infrared drying has numerous advantages over tray drying, including a faster drying rate, higher energy efficiency, higher quality finished goods; a consistent product temperature during the drying process; and a reduced need for air movement over the product [10].

In the Philippines, the drying of sago starch is usually done by using sun-drying, which is inefficient since the temperature cannot be maintained due to unpredictable weather conditions. Moreover, other existing drying technologies known for drying starch and flour, such as drum drying, fluidized bed drying, and pneumatic drying, are not suitable for drying sago starch due to its very high moisture content. With the increasing demand for sago starch, there is a need to develop a high-efficiency dryer, considering sago starch's high moisture content. There's also a need to understand the drying behavior of sago starch under certain drying conditions to design an efficient dryer. Hence, this study was conducted to determine if sago starch can be dried under infrared drying and understand its drying behavior under the said drying method. Specifically, this study aimed to evaluate the drying kinetics of sago starch at different drying temperatures and determine the most suitable drying kinetic model that will describe the behavior of sago starch under infrared drying.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Samples of wet sago starch were obtained from a nearby sago grower. Each holding tray where the samples are placed was weighed using an analytical balance. Sago starch samples were added to the holding tray to determine the weight prior to the start of the experiment. Since the experiment took two (2) days to finish, the sample that will not be used on the first day is placed in the refrigerator at a temperature of 18°C to avoid contamination of the samples. The initial moisture content of the sample is 102 ± 2% (dry basis, db).

2.2 Drying Unit

A developed cabinet-type infrared dryer was used during the drying of sago starch (Fig. 1). The drying chamber has a dimension of 40cmx40cmx22.60cm (Length x Width x Height). It has an aluminum frame to prevent contamination and a 1.5mm galvanized metal sheet covering. All sides of the chamber are covered in heat-insulating material to reflect infrared radiation over the product and to lessen heat loss to the surroundings. The drying room is equipped with linear halogen lamps. These are infrared heating elements and are powered by a 220VAC supply. A PID (Proportional, Integral, Derivative) Controller manages the linear halogen lamps to maintain the drying chamber's temperature. The supporters calibrated the PID Controller to a specific temperature, and the temperature was adjusted with each treatment. A thermocouple is disposed of inside the drying chamber, which is connected to the PID to monitor the inside temperature. An exhaust fan was adapted to extract the evaporated moisture content inside the dryer to the outside.

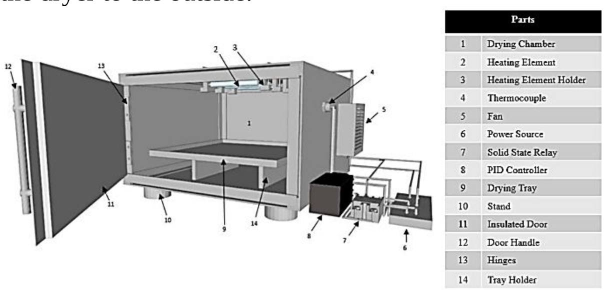

Fig. 1. Cabinet-Type Infrared Dryer

2.3 Drying Procedure

The infrared thin layer drying experiment was conducted at Caraga State University's Main Campus in Ampayon, Butuan City, Philippines. Sago starch's thin layer drying kinetics experimental setup was carried out on a heated plate, and samples were uniformly dispersed in a thin layer [11].

Sago starch thin layer samples were dried at 70°C, 80°C, and 90°C, with three samples for each desired temperature (Table 1). The change in weight of the samples was measured using an analytical balance every 10 minutes (mins) interval until it reached its bone-dry weight (dry matter weight). The analysis used the mean moisture content values [11].

Table 1. Experimental treatment at varying temperatures.

Temperature	**Rep**	**Initial Weight, (g)**	**Initial Moisture Content (MC_i), % (dry basis, db)**
	T1R1	25.70	99.53
T1=70°C	T1R2	29.54	106.14
	T1R3	25.21	106.81
	T2R1	21.01	107.61
T2=80°C	T2R2	28.03	99.50
	T2R3	24.40	100.99
	T3R1	24.15	101.42
T3=90°C	T3R2	23.88	98.83
	T3R3	28.90	98.11

2.4 Mathematical Modelling

Five (5) thin layer drying equations (Table 2) were investigated to find the most suitable drying equations for drying of sago starch.

Table 2. Mathematical models applied to moisture ratio values [12].

No.	Model	Model equations
1	Lewis	MR = exp (-kt)
2	Page	MR = exp (-kt^y)
3	Henderson and Pabis	MR = a exp (-kt)
4	Two Term Exponential	MR = a exp (-kt) + (1-a) exp (-kat)
5	Midilli-Kucuk	MR = a exp (-kt^n) + bt

Two essential parameters were calculated to determine the sago starch's drying characteristics during thin layer drying processes. These include the moisture ratio (MR), which enables to compare and critique of the drying behavior of sago starch, and the drying rate (DR), which uses two successive times of moisture content (MC, db) divided by the change in time (dt) as shown in the following equations below [13].

$$\mathrm{MR} = \frac{\mathrm{M_t - M_e}}{\mathrm{M_o - M_e}} \quad (1)$$

Where:

MC_{db}= moisture content dry basis
M_e= equilibrium moisture content, % (db)
M_o= initial moisture content, % (db)

$$DR = \frac{dMC}{dt} = \frac{MC_{t+dt} - MC_t}{dt} \quad (2)$$

Where:

MC_{t+dt} = moisture content at t_1
MC_t = moisture content at t_2, % (db)
dt = change in time ($t_1 - t_2$), (mins)

The thin layer drying models are evaluated and can be compared using statistical equations. These three statistical equations include the coefficient of determination (R^2), reduced chi-square (X^2), and root means square error (RMSE) [11], which are used to find the best fitted thin layer drying model from the experimental drying data. Notably, the higher R^2 and the lower values of X^2 and RMSE will be considered the best suitable model. The following equations were calculated using equations 3, 4, and 5 [14-15]

$$R^2 = 1 - \left[\frac{\Sigma(MR_{Prd} - \Sigma MR_{Exp})^2}{\Sigma(\overline{MR}_{Prd} - \Sigma MR_{Exp})^2}\right] \quad (3)$$

Where:

R^2 = Coefficient of determination
MR_{pre} = predicted moisture ratio
MR_{exp} = experimental moisture ratio
$\overline{\mathrm{MR}}_{\mathrm{Prd}}$ = mean predicted moisture ratio

$$X^2 = \frac{\Sigma(MR_{Exp} - MR_{Prd})^2}{N-n} \quad (4)$$

$$RMSE = \left(\frac{\Sigma(MR_{Prd} - MR_{Exp})^2}{N}\right)^{\frac{1}{2}} \quad (5)$$

Where:

RMSE = Root Mean Square Error
N = Number of Observations

3. RESULTS AND DISCUSSION

3.1 Drying Behavior of Sago Starch

Sago starch with an average moisture content of 102 ± 2% (dry basis, db) was dried up to its bone-dry weight at different drying temperatures (70ºC, 80ºC, and 90ºC) inside the developed cabinet-type infrared dryer. The average drying time to completely remove the moisture content of the sago starch is 100 mins for 70ºC and 80ºC and 50 mins for 90ºC. A sample of the dried sago starch is presented below (Fig. 2). It was observed during the experiment that sago starch could be dried under the infrared drying method as moisture content was reduced throughout the experiment.

Fig. 2. Sample of dried sago starch

Some of the sago starch samples (Fig. 3). This brown pigment color is not a discoloration of sago starch during the drying process. It was observed that this brown pigment is a sago pit fiber that is joined with the sago starch during the extraction process. According to the locals, it is not new to sago starch extraction since the current process is done manually; hence, the purity of sago starch is affected.

Fig. 3. Dried sago starch with the presence of sago pit fiber

Figures 4-6 show the drying curves of the sago starch at different temperatures in the developed cabinet-type infrared dryer. The moisture ratio and drying were calculated using equations (1) and (2). The drying rate increased in the first 10 mins of the drying process, followed by a continuous decreasing value as the drying time increased. This result is because, at the start of the drying process, the external moisture content of the sago starch can be quickly evaporated since it is directly in contact with infrared radiation. It can also be observed that there is no clear visible sign of a constant rate period (Fig. 4 and 5), and the drying process is entirely in a falling rate period. Identical results were observed by [11] in the drying of saffron under infrared drying, where a constant rate is also absent, and the drying process occurs in the falling rate period. For a product such as sago starch, where external moisture is very high because of its processing operation wherein water is added to separate the starch from the fiber, it increases the external moisture content (unbound moisture). With this, it is recommended that after unbound moisture is removed, the temperature must be reduced to avoid the reduction of starch quality due to high temperature. However, it is evident in Figure 6 that the temperature is a significant factor in the drying of sago starch. As the drying temperature increases and holding other parameters constant, moisture removal increases, resulting in a decreasing drying time. The same result was observed by [16].

3.2 Mathematical Modelling of Drying Curves

Figures 7-9 shows the graphical comparison of predicted moisture ratio using the selected drying models and the experimental moisture ratio at different drying temperatures. The five drying models presented in Table 2 were used for model fitting computations. The moisture content was converted to moisture ratio prior to curve model fitting [11]. Drying model constant were determine and presented in Table 3.

To test the adequacy of each model, the coefficient of determination (R^2), chi-square (X^2) and Root Mean Square Error (RMSE) were determined. The best model describing the thin layer-drying characteristic was chosen as the one with the highest R^2 value and the lowest of X^2 and RMSE value [11]. It can be observed in the table that the accuracy of fitting is affected by the temperatures. These results agree to the results of [17]. As the temperature increases the accuracy of fitting tends to increase for all the models except for Lewis model wherein the accuracy tends to decrease from 70ºC to 90ºC. All the selected drying models have a higher R^2 which is greater than 0.96, which indicates a good fit model. However, midilli-kucuk model shows a better result among all other models with highest R^2 and lowest X^2 and RMSE. This means that among all other selected models, midilli-kucuk model can best describe the drying behavior of sago starch under infrared drying. The model can help in designing a new infrared dryer for sago starch specifically in predicting the desired moisture content with respect to drying time and temperature.

4. CONCLUSIONS

In this study, the drying behavior of sago starch was investigated in the developed cabinet-type infrared dryer. Drying sago starch using infrared drying is possible, as the moisture content is reduced during the drying process. Drying of sago starch under infrared drying occurs in the falling rate period, and the constant rate period is absent. Based on the results of mathematical modelling, midilli-kucuk is the best model for predicting the drying behavior of sago starch. It was also observed in the results that the increase in temperature results in an increase in model fit accuracy. These results could help the designer in designing an infrared dryer. However, even though the experiment showed promising results, the researcher would recommend conducting the same experiment, including the effect of infrared drying temperature on the quality of the sago starch. With this, the designer can design a new dryer that is efficient and enhances or maintains sago starch quality.

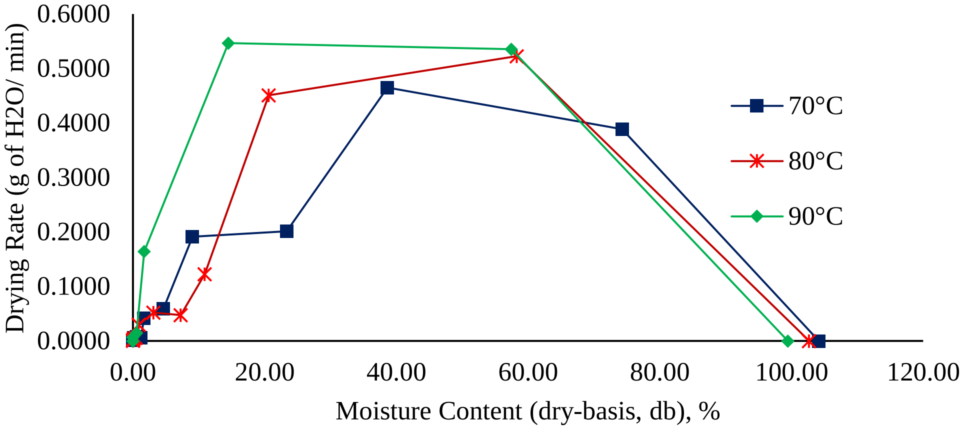

Fig. 4. Variation of drying rate with moisture content at different drying temperatures for sago starch

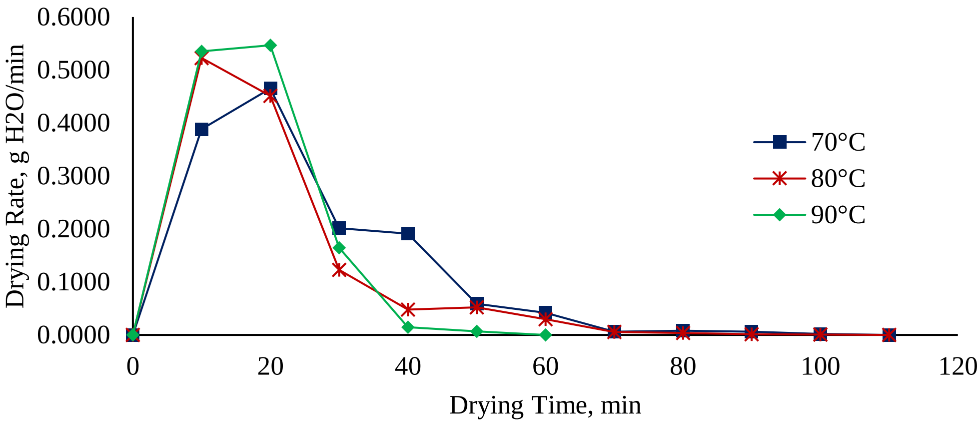

Fig. 5. Variation of drying rate with drying time at different drying temperatures for sago starch

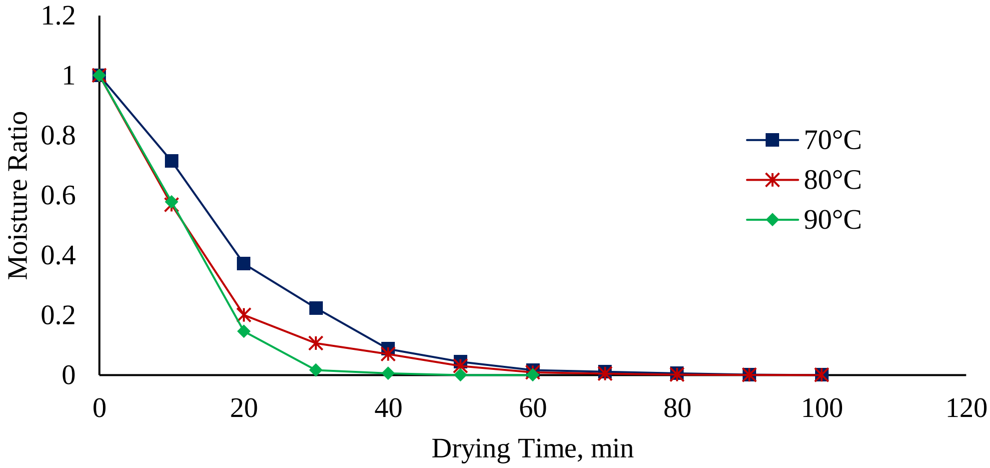

Fig. 6. Variation of moisture ratio with drying time at different drying temperatures for sago starch

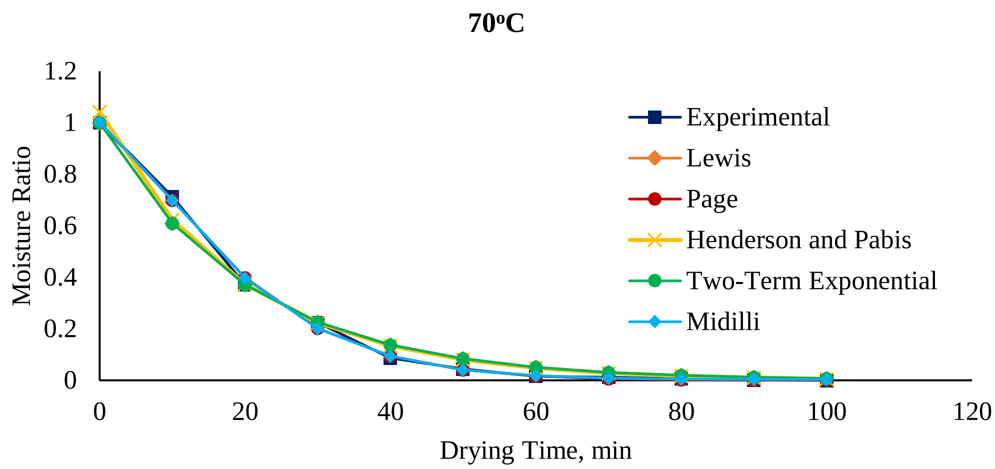

Fig. 7. Graphical Comparison of Predicted Moisture Ratio using Selected Drying Model versus the Experimental Moisture Ratio at 70°C

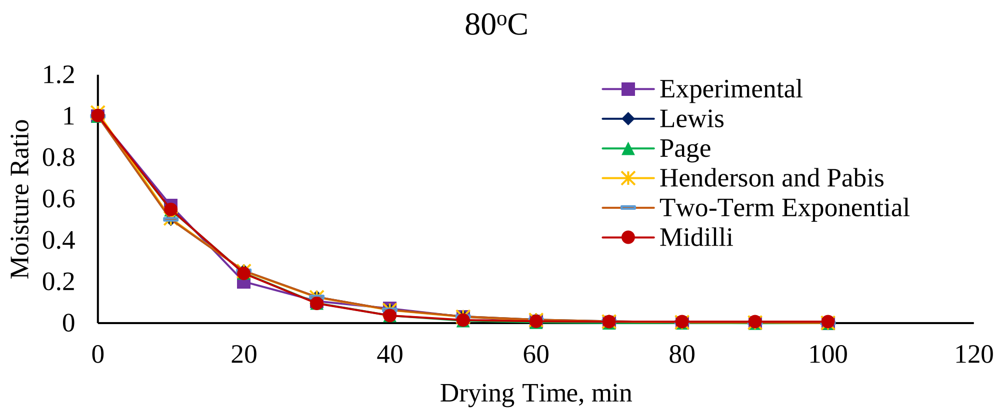

Fig. 8. Graphical Comparison of Predicted Moisture Ratio using Selected Drying Model versus the Experimental Moisture Ratio at 80°C

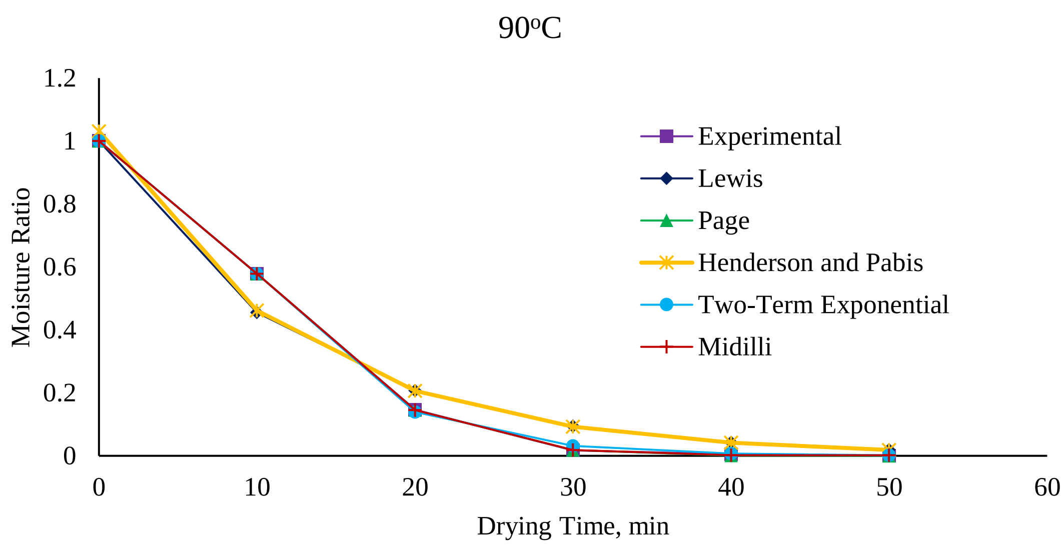

Fig. 9. Graphical Comparison of Predicted Moisture Ratio using Selected Drying Model versus the Experimental Moisture Ratio at 90°C

Table 3. Modelling of Moisture Ratio According to the Drying Time during Drying in an Infrared Dryer for Sago Starch

Drying Temperature (^{0}C)	Model Name	Model Constants	R^2	X^2	RMSE
70	Lewis	k=0.0496	0.9853	0.0021	0.0216
	Page	k=0.0156 y=1.3602	0.9987	8.85E-5	0.0045
	Henderson & Pabis	k=0.0513 a=1.0419	0.9872	0.0051	0.0337
	Two Term Exponential	k=0.0496 a=0.9999	0.9853	0.0021	0.0216
	Midilli-kucuk	k=0.0157 a=1.0031 n=1.3612 b=2.64E-5	0.9987	1.79E-6	0.0006
80	Lewis	k=0.0689	0.9927	0.0001	0.0049
	Page	k=0.0354 y=1.2319	0.9962	0.0013	0.0152
	Henderson & Pabis	k=0.0698 a=1.0165	0.9929	0.0005	0.0092
	Two Term Exponential	k=0.0689 a=0.9999	0.9927	0.0001	0.0051
	Midilli-kucuk	k=0.0340 a=1.0030 n=1.2491 b=7.83E-5	0.9999	0.0001	0.0047
90	Lewis	k=0.0787	0.9686	0.0031	0.0300
	Page	k=0.0084 y=1.8127	0.9999	6.56E-6	0.0013
	Henderson & Pabis	k=0.0804 a=1.0314	0.9699	0.0064	0.0432
	Two Term Exponential	k=0.1475 a=2.6712	0.9997	8.9E-5	0.0051
	Midilli-kucuk	k=0.0084 a=0.9999 n=1.8168 b=3.2E-5	0.9999	2.31E-8	8.21E-5

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