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Effect of Mass on Drying Kinetics of Andaliman (Zanthoxylum Acanthopodium DC.) by Swirl Fluidized Bed Drying: A Mathematical Model

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Abstract. Andaliman (Zanthoxylum acanthopodium DC.) or Batak pepper is often used as a seasoning ingredient in traditional cooking. Andaliman is difficult to consume in faraway areas because it rots quickly and is easily overgrown by fungus. The andaliman needs to be dried to prevent the growth of microbes. The maximum moisture content for dry herbs for the last longer is about 10%. In this study, andaliman was dried by the swirl fluidized bed method at a low temperature of 50 ^{0}C. The low temperature was chosen because andaliman contains various volatile compounds that easily evaporate at high temperatures and reduce its specific aroma. The sample masses for each experiment were 200, 250, and 300 gr. Andaliman grains have an average diameter of 3.1 mm. The moisture content was measured every 10 minutes by sampling. The results showed that the most suitable drying kinetics equation was the Rational model with the general form of the equation $MR=(a+bx)/(1+cx+dx^2)$. The R^2 values for the sample masses of 200, 250 and 300 gr were 0.99959, 0.99878 and 0.99832 respectively, and the average effective diffusion values were 3.06×10^{-9}, 2.57×10^{-9} and 1.97×10^{-9} m^2/s.

INTRODUCTION

Andaliman (Zanthoxylum acanthopodium DC.) is an endemic pepper plant that grows in Tapanuli, Dairi, Simalungun and Karo areas in North Sumatra, Indonesia. The andaliman seeds and branches as shown in Fig. 1. This plant grows well at an altitude of 900-2000 m above sea level with a rainfall of 170-180 days a year. This plant has a distinctive taste and aroma compared to other types of pepper. This plant has a high moisture content, so it cannot be stored for a long time because it will quickly rot. The maximum moisture content to prevent microbial activity in spice plants is less than 10%. Spices are dried at low temperatures.

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FIGURE 1. (a) Andaliman grains and (b) branches

This is related to the volatile substances that are easily damaged by heat and it will reduce the aroma and taste. The low moisture content will allow the spices to be stored for quite a long time. The thermal process is most widely used to dry the material. In this process, the moisture content is removed through evaporation by heating. Moisture from the inside will come out to the surface and then diffuse into the air. The drying rate is influenced by many things, i. e. temperature, humidity and air velocity, thickness, the internal resistance of the material [2]. The drying rate of a material in the drying process is shown graphically in Fig. 2. The drying rate has 3 stages, i.e. the preparation stage, where the drying rate increases. This condition occurs at the beginning of the drying process when the temperature increases from the ambient to the set-up. The constant drying rate is indicated by a constant value. In this period, evaporation occurs only from the surface of the product. This process also takes a short time. Drying at a fall rate begins when the moisture content in the product starts at a critical level. The moisture transfer rate from the inside to the surface is lower than the evaporation rate of moisture from the surface to dry air. The drying rate is significantly influenced by moisture transfer from inside to the surface in the fall rate. The drying is affected by the internal resistance of the product.

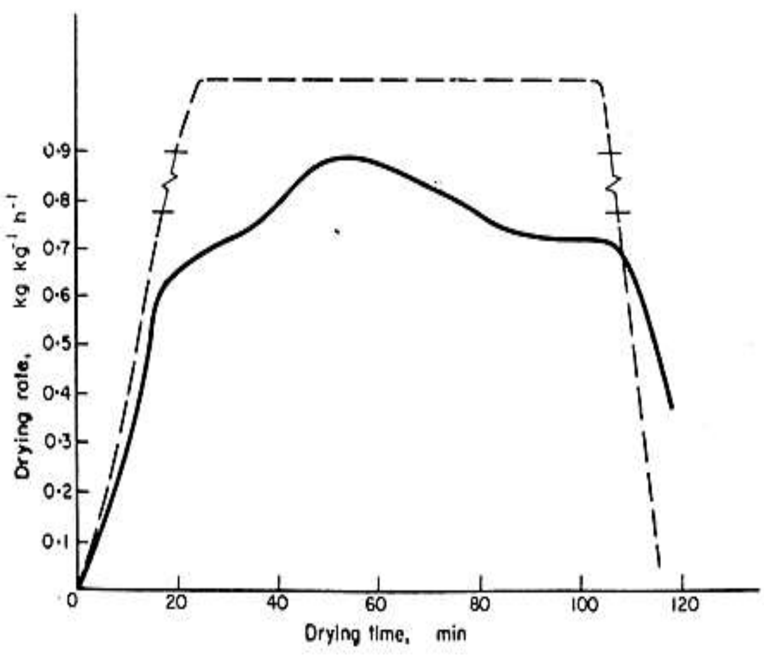

FIGURE 2. Drying rate

Drying is commonly described as the process of thermally removing volatile substance (moisture) to yield a solid product [3]. The drying rate begins the preparation phase, followed by a constant and a falling rate. During the preparation period, the drying rate increases sharply. The stage occurs for a short time until the temperature reaches a steady state. A constant rate period is indicated by a constant drying rate value. In this period, evaporation occurs only from the surface of the product. This process also takes a short time. After this period, drying will be followed by a period of falling rate. There are two periods in the falling rate, i.e. the first and second falling rate periods. Drying in the first stage of falling rate begins when the moisture content in the product starts at a critical level. The moisture transfer rate from the inside of the product to the surface is lower than the rate of evaporation of moisture from the surface to dry air. In this period, the drying rate will be significantly controlled by the moisture transfer rate from the inside to the grain surface. So that drying is affected by the internal resistance of the product.

Swirl Fluidized Bed Drying

The swirl fluidized bed drying is a fluidized bed dryer with a swirling flow. The guide vane generated the air swirl. According to Yilmaz et al. [4], the swirl flow drying can increase the Nusselt number by up to 98% compared to fluidized beds with the non-swirl flow. This data was obtained on the drying of wheat. Another study on swirl flow has been carried out by Sheikoislami et al. [5]. The swirl flow can penetrate the boundary layer on the particle surface so that it can increase heat transfer. As an illustration, the path line of the drying air and the particles in the swirl fluidized bed is shown in Fig. 3.

FIGURE 3. Swirl fluidized bed

Statistical Parameter

Analysis of statistical parameters is needed to determine the mathematical model of drying kinetics. Mathematical models are based on existing and appropriate models. A study like this is very difficult to find. The equation is obtained by regressing the moisture ratio data obtained in the experiment. The most suitable kinetic equation is determined by the value of the correlation coefficient (R). The coefficient of determination (R^2) is the highest. In addition, it also has the lowest reduced Chi-squared value (χ^2) and RMSE [7].

This study aimed to obtain the mathematic model and effective diffusion of drying kinetics of Andaliman grain with the swirl fluidized bed method at various sample masses.

METHOD

The andalimans used in this study were purchased at the Lau Chi market in Medan, North Sumatra. Andaliman is first sorted so that it is still fresh. The old or rotten are discarded. Andaliman before and after drying is shown in Fig. 4.

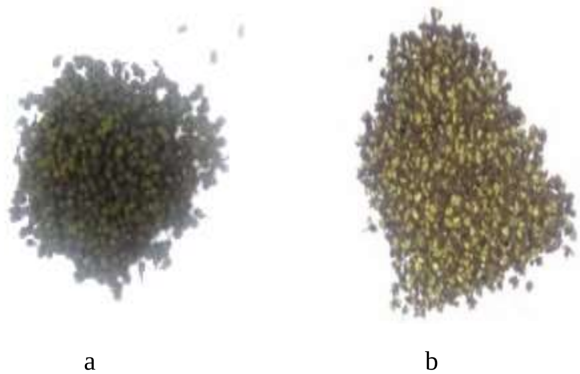

FIGURE 4. Fresh andaliman (a) before and (b) after drying

The swirl fluidized bed dryer used is shown in Fig. 4. The ambient air is sucked in by a 550-watt blower and then heated by two 400-watt heaters. Hot air is pushed into the drying chamber. A thermostat controls the temperature of the drying air. The drying chamber is equipped with a transparent acrylic plate to be able to see the position and movement of the andaliman grains. The drying chamber has a total height of 950 mm, an inner diameter of 60 mm, and an outer diameter of 115 mm. The guide vanes are made of 5 pieces of steel plate with a thickness of 1 mm. The guide vanes are arranged around the axis. Between one blade and the next, there is a gap for air to flow. The dryer is shown in Fig. 5. At the chamber outlet, a filter is installed to prevent andaliman grains from leaving the drying chamber. The temperature and relative humidity data logger are placed below the vane. Likewise, on the exit of the chamber.

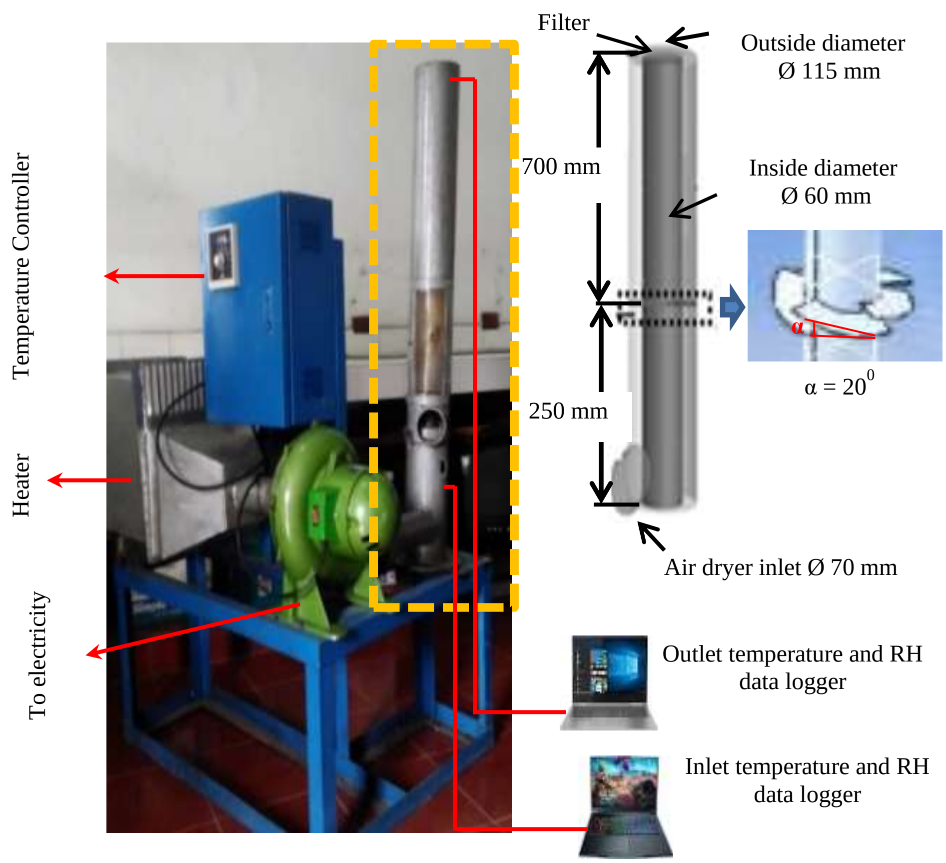

FIGURE 5. Experimental set-up of swirl fluidized bed drying

The measurement results show that the airflow velocity at the outlet is 6 m/s. This value is obtained from preliminary testing. The formulation proposed by Chitester et al. [8] in Kunii and Levenspiel [9] for coarse particles cannot fluidize particles because the value is too small. This velocity is capable of fluidizing andaliman grains, which have an average diameter of 3.1 mm. Hot air is used to dry the andaliman at a temperature of 50 ^{0}C and is controlled by a temperature controller. The sample masses of each experiment were 200, 250, and 300 gr.

During drying, 2 gr of andaliman fruit was taken from the drying chamber every 10 minutes to measure the moisture content. The sample was put in a sealed plastic bag. After drying was completed in 240 minutes, all samples were dried in an electric oven for 3 hours and 105 ^{0}C to calculate the moisture content. Moisture content is calculated on a wet basis with the equation:

$$Mc = \frac{M_{H2O}}{M_{total}}\ x\ 100\% \tag{1}$$

where M_{H2O}: mass of moisture (gr), M_{total}: total mass (gr) The drying rate is calculated by the equation below

$$DR = \frac{MC_{t0} - MC_{t1}}{\Delta t} \tag{2}$$

where MC_{to}: moisture content at t = 0, MC_{t1}: moisture content after t_0

The coefficient correlation value of R, which is closest to 1, is the best equation model because it has the smallest deviation from the test results. The value of R is the square root of the coefficient of determination. The coefficient of determination, R2 is calculated from equation (3):

$$R^2 = 1 - \left[\frac{\sum\left(MR_{Prd} - \sum MR_{Exp}\right)^2}{\sum\left(\overline{MR_{Prd}} - \sum MR_{Exp}\right)^2}\right] \tag{3}$$

where R: coefficient correlation, MR_{Prd}: predicted moisture ratio (non-dimensional), MR_{Exp}: moisture ratio of the experiment (non-dimensional), $\overline{MR_{Prd}}$: average moisture ratio predicted

The Root Mean Square Error (RMSE) is the magnitude of the error rate of the predicted value. The predictive value will be more accurate if the RMSE value is closer to 0. The RMSE value is calculated by equation (4)

$$RSME = \left(\frac{\sum\left(MR_{Prd} - MR_{Exp}\right)^2}{N}\right)^{\frac{1}{2}} \tag{4}$$

The reduced chi-square was used in the goodness of fit test. The square root is called the regression standard error. The smaller the chi-square value, the better the model/equation obtained. Chi-square (χ^2) is calculated from equation (5)

$$\chi 2 = \frac{\sum\left(MR_{Exp} - MR_{Prd}\right)^2}{N-n} \tag{5}$$

where χ^2: reduced chi-square, N: size of observation, n: size of the parameter, integer number, positive.

The moisture ratio was calculated from the equation:

$$MR = \frac{M_t}{M_o} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}}{4L^2}\ t\right) \tag{6}$$

For the long time drying, the above equation can be simplified to

$$ln\,MR = ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4L^2}t \tag{7}$$

where L: half-length of material, D_{eff}: effective diffusion, n: positive number

Effective diffusion (D_{eff}) describes the rate of movement of moisture content from the inside to the surface of the material. The effective diffusion coefficient is based on the average cross-sectional area open to diffusion and the distance traveled by the molecules in the porous medium. The effective diffusion coefficient is the slope of the curve, which can also be obtained by plotting the ln MR value and drying time. The D_{eff} value is calculated using the equation.

$$D_{eff} = slope\ \ x\ \frac{4L^2}{\pi^2} \tag{8}$$

In this study, the moisture ratio was calculated from 6 equation models as shown in Table 1. From these model equations, CurveExpert Professional 2.3.0 software was used to see the values of the correlation coefficient (R^2). After that, statistical analysis was carried out to see the values of the Root Mean Square Error (RMSE) and Chi-Square (χ2) for each equation with MS-Excel. This is done to obtain the best-suited drying kinetics model.

TABLE 1. Drying kinetics model

No	Model	Equation	Reference
1	Rational Model	$MR = \frac{a + bx}{1 + cx + dx^2}$	NIST [10]
2	DR-Hill	$MR = \alpha + \frac{\theta x^\eta}{\kappa^\eta + x^\eta}$	CurveExpert [11]
3	Bleasdale	$MR = (a + bx)^{-1/c}$	Seber and Wild [12]
4	Wang and Singh	$MR = 1 + ax + bx^2$	Akpinar [13]
5	Simplify Fick's Diffusion	$MR = a\exp(-c\left(\frac{x}{2L}\right))$	Diamante and Munro [14]
6	Logistic Power	$MR = a/(1 + (x/b)^c)$	CurveExpert [11]

Note: a, b, c, d, L, Ķ, θ, η: constants of the equation, x: time

RESULT AND DISCUSSION

Outlet Temperature

The heat contained in the drying air is the energy used to evaporate the moisture contained in the andaliman grains. The amount of energy contained in the drying air is indicated by the temperature. In this study, the drying air temperature on the outlet side will be lower than on the inlet side because it is used to evaporate the moisture content.

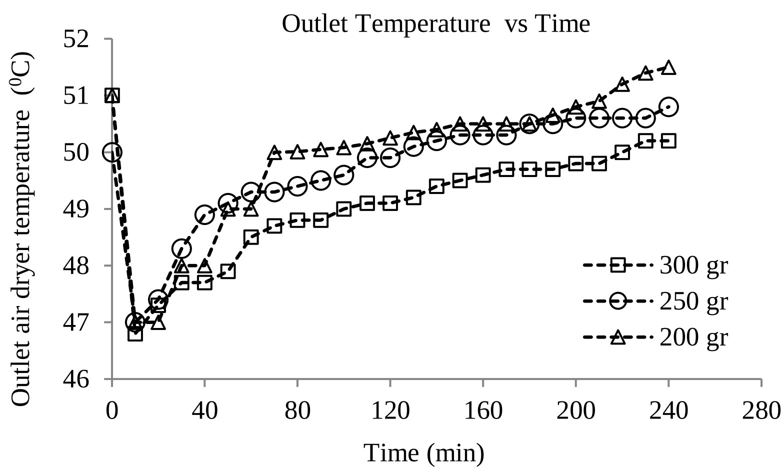

FIGURE 6. Outlet temperature

The drying air temperature measured at the outlet position for the experiments carried out is shown in Fig. 6. The temperature in the experiment with a mass of 300 gr looks lower than the others. This indicates that in this experiment, more moisture was evaporated than in the experiments with masses of 250 and 250 gr.

Outlet Relative Humidity

The relative humidity is the ratio of the existing humidity to the maximum possible humidity in the air. The higher the value, the higher the moisture content in the air. In this experiment, the more moisture evaporated, the higher the relative humidity. The position of the RH meter in this experiment is on the outlet side of the chamber. The amount of relative humidity for each measured experiment is shown in Fig. 7. The experiment with a sample mass of 300 gr makes the humidity of the drying air have the highest humidity compared to other experiments. This is in line with the measurement of temperature where the temperature measured is lower. This indicates that the moisture in the experiment with a mass of 300 g evaporated more than the experiment with a mass of 200 and 250 gr.

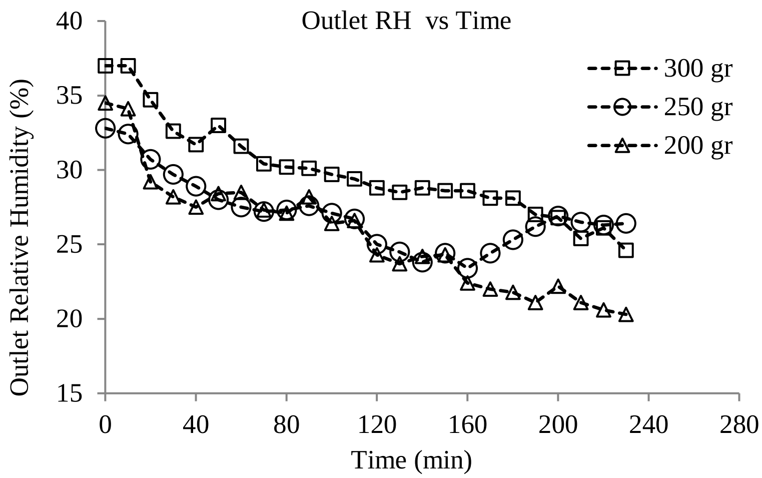

FIGURE 7. Outlet Relative Humidity

Moisture Content

The moisture content of the experiment is shown in Fig. 8. It can be seen that the sample with a mass of 200 gr dries faster than those of 250 gr and 300 gr. The difference is not too significant for the interval of 50 gr. After drying for 180 minutes, the change in moisture content began to slow down. The difference between each sample in Fig. 8 looks relatively proportional. The decrease in moisture content is slower due to the less moisture content in andaliman grains.

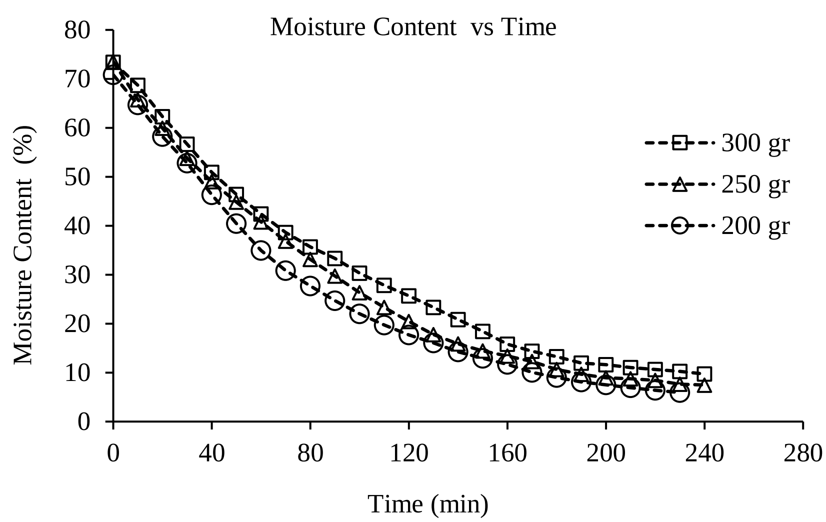

FIGURE 8. Moisture content vs time

Moisture Ratio

Changes in the moisture ratio during the experiment are shown in Fig. 9. The moisture ratio needs to be seen considering that all samples' initial moisture content is not the same. Thus, a number is needed that can accommodate these differences through changes in the moisture ratio. The moisture ratio in the initial conditions is always 1. Fig. 9 shows that the decrease in the moisture ratio of the three samples is relatively proportional, although not too ideal. The sample with the smallest mass decreases faster in equilibrium conditions. There is no decrease in moisture content because the relative humidity of the air is the same as the humidity on the andaliman surface. In these conditions, the moisture will be difficult to diffuse into the air. The moisture content will be constant than the heavier ones. It corresponds to a change in moisture content, as shown in Fig. 8. The decrease in the moisture ratio also slowed from the 180th minute.

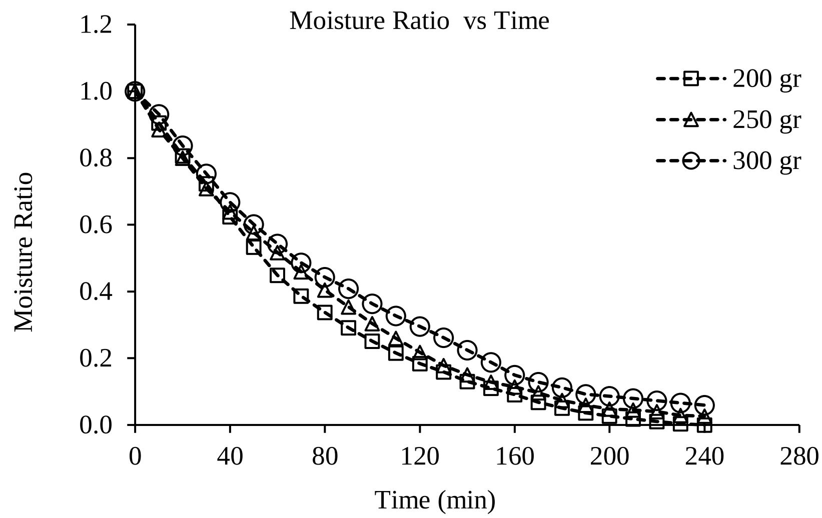

FIGURE 9. Moisture ratio

Drying Rate

The drying rate is shown in Fig. 10. In general, the drying rate decreases during the process. The constant rate period occurs in a short time, as indicated by the 200 g sample. The period of falling rate is dominant even though the moisture content is still high. It is due to the difficulty of the air in it moving to the surface of the andaliman grains. It occurs due to andaliman's peel, so that water will have difficulty moving to the peel's surface. The highest drying rate was produced by the heaviest sample, which was a sample of 300 gr.

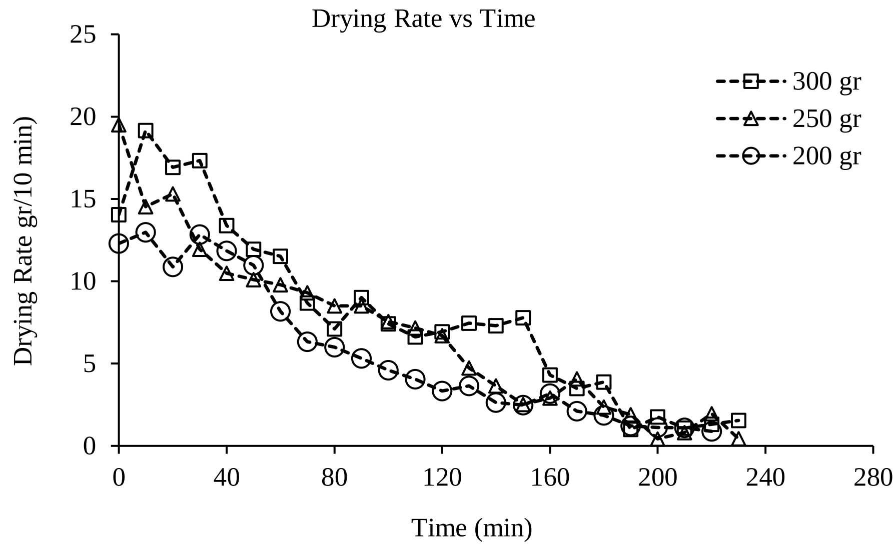

FIGURE 10. Drying rate vs time

It is due to the mass being heavier, so the mass of water content is more. Graphical models also occur in drying shrimp by Murali et al., [15], and kiwi fruit by Ozgen and Celik [16]. The drying rate value decreases until it approaches zero at the end of drying. At this equilibrium condition, the moisture content is approximately 10%, as shown in Fig. 11.

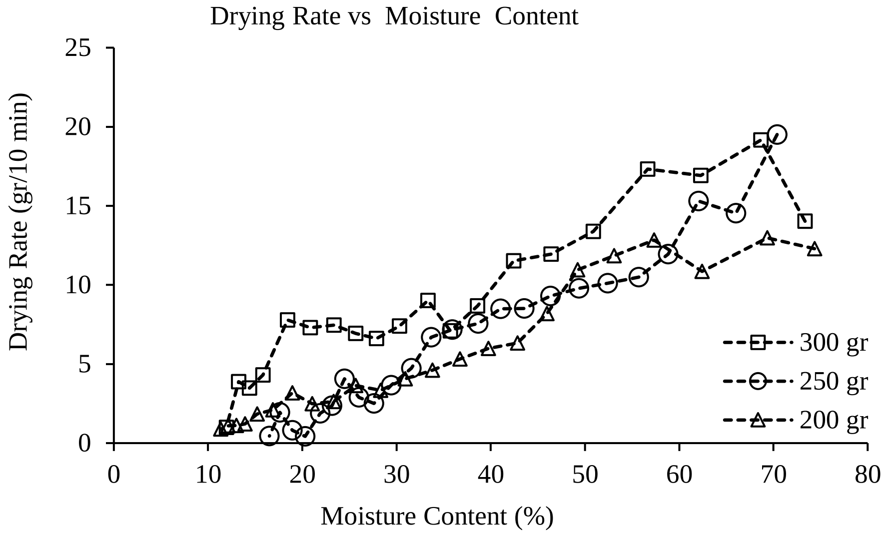

FIGURE 11. Drying rate vs moisture content

Statistical Parameter

Table 2 shows the regression results obtained from the 6 proposed equation models. Table 2 shows that the best regression is Rational model, followed by the DR-Hill and Bleasdale models. The rational model has an R^2 value of 0.99959; 0.99878 and 0.99832 for each sample mass of 200, 250, and 300 gr, respectively. The RMSE value obtained is also quite small, i. e., 0.0799, 0.07451, and 0.05467, respectively. The RMSE values obtained are also quite small, i. e. 0.00696, 0.00603 and 0.00325, respectively. The equation of the rational model is a comparison between two polynomial functions. This model has the general form $MR=(a+bt)/(1+bt+dt^2)$, Cinkir and Stef [17]. The effective diffusion values obtained for each mass of 200, 250 and 300 g were 3.06 x 10^{-9}, 2.57 x 10^{-9} and 1.97 x 10^{-9} m^2/s. The larger value shows that the drying is faster. In this study, the value is not much different from the results obtained by Ozbek and Dadali [18], which is in the range of 10^{-7} to 10^{-8} m^2/s on drying mint leaves using a microwave.

TABLE 2. Evaluation of statistical parameter

Model	Mass (gr)	Coefficients	Std Error	R^2	RMSE	χ^2
Rational Model	200	a = 1.007397E+00, b = -4.203821E-03, c = 5.80861E-03, d = 7.78120E-05	0.00658	0.99959	0.07999	0.00696
	250	a = 9.85184E-01, b =-3.80735E-03, c = 5.02691E-03, d = 5.34068E-05	0.01103	0.99878	0.07451	0.00603
	300	a = 1.00691E+00, b = -3.44296E-03, c =5.73340E-03, d = 3.09844	0.01276	0.99832	0.05467	0.00325
DR-Hill	200	alpha = 9.93943E-01, theta = -1.17019E+00, etha = 1.41044E+00, kappa = 6.73419E+01	0.00517	0.99975	0.00611	0.00004
	250	alpha = 9.79066E-01, theta = -1.22076E+00, etha = 1.30689E+00, kappa =8.36693E+01	0.01603	0.99745	0.01482	0.00024
	300	alpha = 1.00019E+00, theta = -1.29034E+00, etha =1.21447E+00, kappa = 9.89503E+01	0.01355	0.99811	0.01240	0.00017
Bleasdale	200	a = 9.99998E-01, b = 4.74754E-07, c = 3.26784E-05	0.02511	0.99380	0.02428	0.00064
	250	a = 9.98190E-01, b = -2.76260E-03, c = =2.70840E-01	0.00817	0.99931	0.00774	0.00007
	300	a = 9.99999E-01, b = 4.27398E-07, c = 3.850019E-05	0.02070	0.99537	0.02605	0.00074
Wang and Singh	200	a = -9.79833E-03, b = 2.431766E-05	0.02829	0.99176	0.02678	0.00078
	250	a = -9.150342E-03, b = 2.18029E-05	0.01666	0.99699	0.01689	0.00031
	300	a = -8.27591E-03, b = 1.84811E-05	0.01621	0.99703	0.01583	0.00027
Simplify Fick's Diffusion	200	a = 1.05663E+00, c = 7.43367E-01, L = 2.55847E+01	0.02511	0.99380	0.02410	0.00063
	250	a = 1.03514E+00, c =1.48090E+00, L = 5.802417E+01	0.02578	0.99310	0.02473	0.00066
	300	a = 1.037761E+00, c = 7.67999E+00, L = 3.45917E+02	0.02069	0.99537	0.01970	0.00042
Logistic Power	200	a = 9.45753E-01, b =5.67259E=01, c = 2.06993E+00	0.03071	0.99068	0.02898	0.00091
	250	a = 9.18116e-01, b = 6.55841E+01, c = 2.06108E+00	0.03438	0.98773	0.03324	0.00120
	300	a = 9.50711E-01, b = 7.02706E+01, c = 1.84906E+00	0.03121	0.98946	0.41973	0.19149

CONCLUSION

In the study, conclusions were obtained, i.e.:

- The falling rate period dominates drying until the moisture content is about 10%.
- The most suitable drying kinetic equation is the Rational Model with the general form of MR = (a + bx)/(1 + cx + dx^2).
- The R^2 values for the sample masses of 200, 250 and 300 gr were 0.99959, 0.99878 and 0.99832 respectively, and the average effective diffusion values were 3.06×10^{-9}, 2.57×10^{-9} and 1.97×10^{-9} m^2/s

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