J Ther Eng, Vol. 11, No. 4, pp. 1135–1147, July, 2025

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000968

Research Article

Kinetics and mathematical model of sugarcane bagasse drying in laboratory scale rotary dryer

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ARTICLE INFO

Article history
Received: 09 May 2024
Revised: 12 November 2024
Accepted: 19 November 2024

Keywords:
Bagasse; Drying; Mathematical Models; Moisture Ratio; Rotary Dryer

ABSTRACT

Sugarcane is the primary source of natural sweeteners that are always needed. North Sumatra is a province in Indonesia with a population of 14.8 million. It consumes as much as 144,323 tons of sugar per year. The existing sugar factory can produce 47,122 tons. One of the by-products of sugar factories is bagasse, which is used as fuel in boilers and has a moisture content of about 50%. Dried bagasse can be used for various purposes, such as fuel, paper, particle board and feedstock. On the other hand, the boiler exhaust gas in a sugar mill has a temperature of around 150-200 °C. This bagasse can be dried before being used in a boiler to save consumption. Theoretically, this heat can be used to dry bagasse. The study aimed to obtain a drying kinetic model, the occurrence of changes in the drying stage of the falling rate, effective moisture diffusion, and errors between the kinetic model and the experiments on drying with the rotary dryer method. Things like this have been difficult to find until now. This study was conducted through an experiment of drying sugarcane bagasse using a rotary dryer on a laboratory scale. The temperatures used were around the exhaust gas temperature, namely 140, 160, 180, and 200 °C and the drum rotation was 3 rpm. The sample masses are 100, 125, and 150 gr, with a length of 3 cm. The results show that the Wang and Singh model is the most appropriate kinetic model due to the highest correlation coefficient and the lowest Root Mean Square Error and chi-square (χ^2) values. Another result obtained was that since drying, only the drying rate of the first and second stages can be seen. The change in drying rate from the first to the second stage is faster when the temperature is higher and the sample mass is less. This change occurred around the 12th to 22th minute. The effective moisture diffusion definition for 100, 125, and 150 gr sample masses at 200 °C drying temperature were 2.72 x10^{-5}, 2.60 x 10^{-5}, and 1.93 x 10^{-5} m^2/s, respectively. The error between the experimental results and the Wang and Singh model mainly were below 5%.

Cite this article as: Simanjuntak ME, Widyawati PS. Kinetics and mathematical model of sugarcane bagasse drying in laboratory scale rotary dryer. J Ther Eng 2025;11(4):1135–1147.

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This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkilic

Published by Yıldız Technical University Press, İstanbul, Turkey

INTRODUCTION

Sugar as a sweetener is one of the basic human needs. The need for sugar will increase along with the increase in population, welfare and mobility/physical activity. Sugar is beneficial in providing the body with energy in a short time. Sugar is widely used in the food industry (Singh et al., 2020). The plants can produce sweeteners such as sugar cane, stevia, yacon, coconut, maple, dates, corn and cassava. Sugar cane is the most widely used plant to produce sweeteners. The most widely used natural sweetener is made from sugar cane. North Sumatra, with a population of around 14,800,000 people in 2020, is one of the provinces in Indonesia as a sugar producer. The amount of sugar produced is about 144,323 tons per year, but it is still insufficient to cover the demand. Sugar cane plantations in North Sumatra are located in the Langkat district and Binjai City. There is one sugar factory in the Langkat Regency area, Indonesia. The area of sugar cane plantations owned by the people and the state and sugar production in Indonesia are shown in Table 1.

While making sugar cane, bagasse will be produced as waste used as fuel in the boiler. The moisture content of this bagasse is about 50%. It is still too high used as fuel. On the other side, the exhaust gas in the boiler chimney has a temperature of 150 – 200 °C [2], [3]. Utilizing exhaust gas temperatures that are still high enough to dry bagasse will be very useful for saving energy in sugar factories. Sugarcane bagasse used in the boiler is about 50% of that produced by the sugarcane mill. The rest can be used for various other purposes. Sugarcane bagasse can be used as fuel in boilers, particle boards, paper, furfural, and feedstock [4]. For some of the uses above, it is better to dry the bagasse before using it. Other uses still in the research stage include making bioethanol, carbon, and coagulant. Drying is an attempt to reduce the moisture to improve the material's quality. The drying of bagasse is intended to increase the calorific value (as fuel in the boiler), reduce the growth of fungi (as animal feed), prevent decay (in making particle board), and shorten storage (in making pulp). Drying is an attempt to reduce the moisture content in a material to upgrade the material's quality. The drying of bagasse is done to increase the calorific value (as fuel in the boiler), reduce the growth of fungi (as animal feed), prevent decay (in making particle board), and shorten storage (in making pulp) (Table 1) [1].

Bagasse dryers that have been studied use microwaves, vertical fluidized beds, cyclones, tube dryers and polyhouses. Simanjuntak and Widyawati, 2020 [5] dried bagasse utilizing a microwave to determine the effect of the power used. Meanwhile, [6] used a fluidized bed vertical dryer to dry sugarcane bagasse. The study examines the impact of the cyclone shape and operating parameters on determining the residence time and changes in particle moisture ratio. Wheatly et al., 2020 [7] examined optimizing the dimensions of industrial-scale rotary dryer tubes. Other research on bagasse is mainly directed at its function as bioenergy [8], [9], [10] and biomaterial [11] and [12].

Biomass dryers widely used on industrial scale are sun drying, flash/pneumatic dryers, and rotary dryers [13]. The disadvantage of sun drying is that it depends on the weather. Flash/pneumatic dryers use hot air flowing at 25 m/s. Thus, this dryer requires a lot of hot air, so it is more wasteful regarding heat consumption. According to Delele et al., 2014 [14], the advantages of rotary dryers are suitable for products of various sizes and shapes. In addition, it can be used in low to high-humidity environments and is suitable for sticky and difficult-to-flow materials. Rotary dryers are also widely used for extensive materials drying (> 10 mm) or materials that do not pose a problem during the handling process [15]. The weakness is the high capital and maintenance costs. It cannot be used for brittle materials. Commonly dried materials are biomass, animal feed, by-products, waste, granules, herbs, and vegetables. The industry has widely utilized rotary dryers for fertilizers, seaweed, cement, and minerals such as lead and zinc. Besides that, this dryer type is also used to dry various agricultural products such as rice, corn, coffee beans, and peanuts [4]. Drying in a rotary dryer takes place in a rotary drum. This tool consists of a cylindrical shell that rotates at a certain speed and is supported by bearings. The feed is entered from one side and exits from the other side. Hot air can flow in the same direction or opposite to the feed flow. This hot air can directly or indirectly contact the dried material. The drying process can take place in a continuous or batch system. Considering some of the above things, further study into drying bagasse in a rotary drying is quite interesting.

Researchers use statistical analysis to obtain a drying kinetic model. Many studies have been conducted to

Table 1. The total area of sugarcane plantations and sugar production in North Sumatera

Year	People's Plantation		State Plantation		Total	
	Area (ha)	Production (ton)	Area (ha)	Production (ton)	Area (ha)	Production (ton)
2017	962	939	3,549	8,643	4,511	9,582
2018	905	950	3,249	8,725	4,154	9,675
2019*	3,164	6,514	3,375	10,725	6,539	17,239

*In 2019, based on prediction results

determine the drying kinetic model that occurs. To get the model is preceded by statistical analysis. This tool obtains correlation coefficients, RMSE, Chi-square and several other parameters. The moisture ratio is obtained from the moisture content. Then, those data are input into the statistical equations. The most appropriate kinetic model must meet requirements such as how the value of the statistical parameters.

Drying kinetics describe the mechanism of microscopic and macroscopic heat and mass transfer as long as the drying process, the type of dryer, the drying conditions, and the characteristics of the material influence it. Studying the kinetics of drying is useful for choosing the proper drying method and controlling the drying process. It is important for process engineering and optimization [16]. Shah dan Joshi, 2010 [17] researched the modeling bagasse drying kinetics using a microwave. The most appropriate kinetic model is the Midilli model. Szadzińska and Mierzwa, 2021 [18] researched the drying kinetics of white mushrooms. This study stated that Page and Weibull's mathematical model is the best applied to microwave drying. Kadam, 2015 [19] suggested that the drying models of Wang and Singh is the most suitable for convective drying of brown seaweed. Selvi, 2020 [20] stated that using an infrared dryer, the Midili-Kucuk and Verma drying kinetics model is most suitable for drying linden leaves. Khaloahmadi et al., 2023 [21] stated that the drying model of logarithmic was the most suitable for drying homemade food waste on a cabinet dryer. Meanwhile, the two-term drying model is the best for drying rubber sheets using sunlight [22]. In addition, there are other studies regarding the kinetics of drying biomass, such as taxus chinensis [23], municipal sewage sludge [24], and acacia wood [25]. From the existing literature, research on drying sugarcane bagasse using a rotary dryer is primarily about moisture content and drying rate. A'yuni et al. 2024 [26] reported that the Page, Newton, and Logarithmic models were the most suitable for drying rice in a rotary dryer. Also, they noted that the more samples were dried, the more efficient the energy consumption would be. Drying was done at 56.4 °C and the energy efficiency was 15.64%.

Moisture effective diffusion explains how quickly moisture diffuses into the surrounding air per unit area and time. This speed will be influenced by various factors such as differences in temperature, surface air pressure with the environment, differences in water content, air speed used and others. Simanjuntak dan Widyawati, 2022 [27] dry bagasse in a microwave and the most suitable model is the rational model. The study also reported D_{eff} of 1.044 x 10^{-7} to 2.009 x 10^{-7} m^2/s, the specific energy consumption of 2.1 - 3.1 kWh/kg and the activation energy of 4.789 W/gr. Research on drying kinetics and effective moisture diffusion with variations in mass and temperature is still difficult to find.

It is very likely to cause errors in every data collection in research. The errors in research can be errors in the tool or data collection and data analysis. These two things are substantively different. Akan and Unal, 2021 [28] reported various data errors in oil-heated convection drying systems. The data errors include measuring sample thickness, thermocouple temperature, wind speed, mass and relative humidity. The most significant error was the temperature measurement; the study's total error was 4.8%. Error analysis is used to explain how accurate the data predictions made are compared to the existing data. If the predicted data is getting closer to the existing data, the error that occurs is very small and can be ignored. If the error is significant, the prediction is wrong and needs to be corrected. However, error analysis carried out in drying research is still rarely found in the open literature. In addition, determining the drying stage, which includes constant rate, first and second stage falling rate is also difficult to find in open literature. This gap is an opportunity to be discussed further in this study.

This literature gap is an opportunity to find interesting topics for further research. This study uses a laboratory-scale rotary dryer based on several previous researchers' proposed equations to determine the bagasse drying kinetics model mathematics.

METHODOLOGY

Experimental Setup

This study obtained the sample from sugar factories located around the city of Medan. The sample was chopped to around 3 cm. The mass of the experimental sample was 100, 125, and 150 gr [17]. The sample is put in the basket, which rotates at 3 rpm according to the dryer's capabilities. It was measured by a Lutron DT1236L photo-contact tachometer with an accuracy of 0.05% and a detecting distance of 5-200 cm. Sai, 2013 [15] uses a rotational speed of 5 - 15 rpm, while Chia and Chog, 2015 [29] use 1-3 rpm. The temperatures used are 140, 160, 180, and 200 °C, referring to the boiler exhaust gas temperature. The temperature is set by a knob on the dryer and measured again by a mercury thermometer with a range of 0-250 °C. Singh et al., 2018 [30] state that the exhaust gas temperature can reach 300 °C, while Wheatly et al., 2020 [7] mention 140 -155 °C temperatures. The flue gas actual temperature in many boilers is 180 – 200 °C [31].

The rotary dryer is modified from a commercial electric oven Oxone Type OX 8330 with a volume of 30 ltr. The oven already has a rotating shaft with 3 rpm. The basket is made from wire mesh so that the hot air can freely heat the sample, which is placed inside while rotating. Two heaters are placed at the bottom and top of the sample so the heat is evener. The operator can adjust the temperature by the button. The experimental setup is shown in Figure 1.

During the drying process, the sample mass was weighed every 2 minutes with the basket and then put back into the dryer as soon as possible. Weighing was stopped after the sample mass was constant. The mass balance used is SF-400C which has an accuracy of 0.01 gr.

Formulations

There are quite a lot of studies on Statistical analysis to obtain drying kinetics that have been done. Ismail et al. 2016 [32] did it on drying nectarines using the sun, hot air, microwave and infrared drying techniques; Doymaz and Kipcak, 2019 [33] and Halig et al., 2023 [34] also did it. The moisture ratio is the ratio of humidity, which is a dimensionless number representing the moisture content in the dried material. The moisture ratio is needed to obtain a mathematical drying kinetics model. The value of the moisture ratio that remains in the dried material for each sample mass measurement is calculated using equation (1).

$$MR = \frac{M_b - M_{eq}}{M_i - M_{eq}} \quad (1)$$

Where MR is the moisture ratio, M_b is the moisture content as wet basis, M_i is the moisture content in the initial condition, and M_{eq} is the moisture content on the equilibrium condition. For M_{eq} is too small, the equation (1) can be expressed as:

$$MR = \frac{M_b}{M_o} \quad (2)$$

The MR values of each experiment were regressed using CurveExpert software to get the correlation coefficient (R^2) value. The correlation coefficient shows the relationship between the measurement and predictions based on the

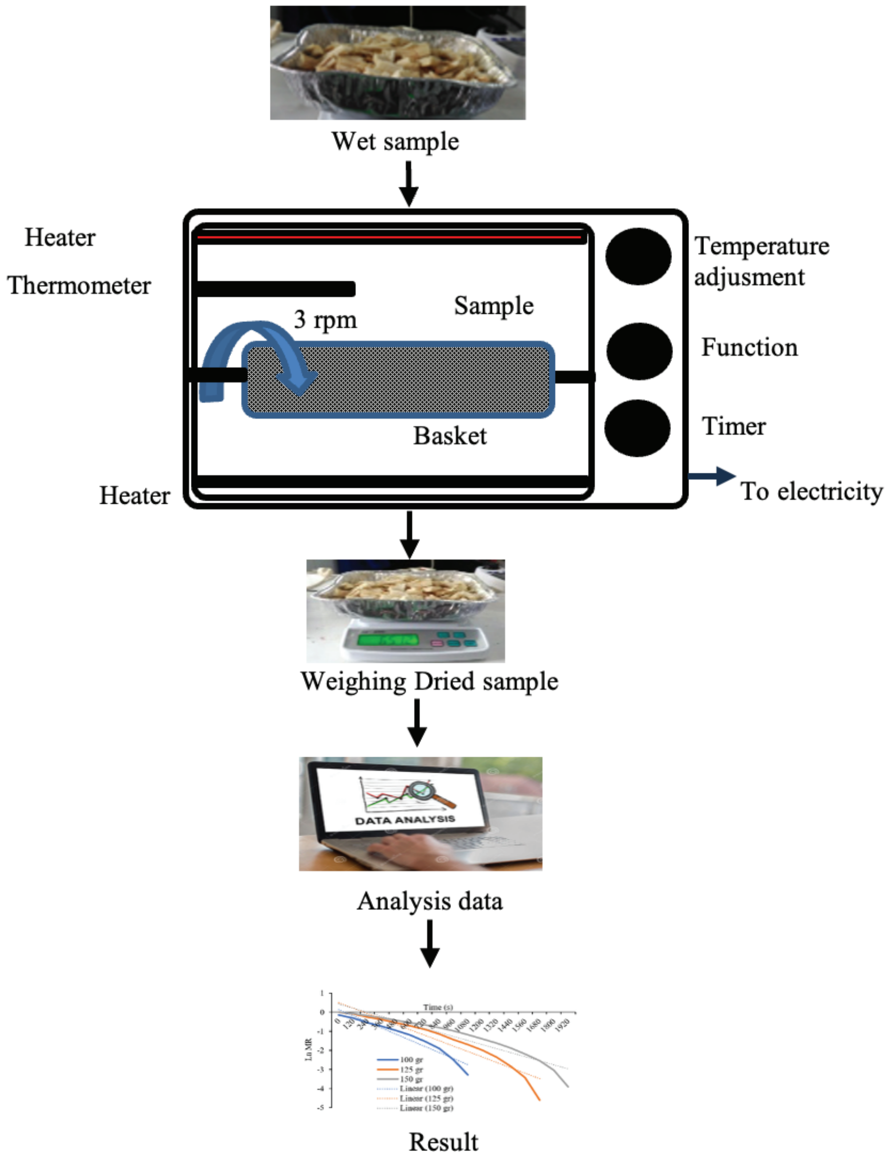

Figure 1. Experimental setup.

Table 2. Drying kinetics equation models

No	Model	Equation	Ref.
1	Pages	$MR = exp(-kt^y)$	[35]
2	Modified Page	$MR = exp(-(kt)^y)$	[36]
3	Wang and Singh	$MR = 1 + at + bt^2$	[19]
4	Logarithmic drying	$MR = a\exp(-kt) + c$	[37]
5	Two terms	$MR = a\exp(-k_1 t) + b\, exp(-k_2 t)$	[38]
6	Verma	$MR = a\exp(-kt) + (1 - a)\exp(-gt)$	[20]
7	Weibull drying	$MR = e^{\left(-\left(t/\alpha^{\beta}\right)\right)}$	[18]

k = constant, t = time, y = constant, a = constant, b = constant, g = constant, k_1 = constant 1, k_2 = constant 2, g = constant, α = Weibull model scale parameter, β = shape parameter

equations obtained. The value of the R^2 closest to 1 is the best equation model due to the slightest deviation from the experiment data.

This study calculated the moisture ratio from 7 model equations, as shown in Table 2. Other researchers often use these equations to obtain a mathematical drying kinetics model. The R^2 is calculated based on equation (3):

$$R^2 = 1 - \left[\frac{\sum(MR_{Pred} - \sum MR_{Ex})^2}{\sum(MR_{Pred} - \sum MR_{Ex})^2}\right] \quad (3)$$

Where MR_{Pred} is the moisture ratio predicted, MR_{Ex} is the moisture ratio experimental, and $(\overline{MR_{Pred}})$ is the average moisture ratio predicted.

The next step is calculating the Root Mean Square Error (RMSE) and Chi-Square (χ^2) values for each experiment using MS Excel. Then, the most appropriate drying kinetics model is obtained.

RMSE is the magnitude of the error rate prediction. The prediction data will be accurate when the RMSE is closest to 0. The RMSE value is calculated according to equation (4).

$$RMSE = \left(\frac{\sum(MR_{Prd} - MR_{Ex})^2}{N}\right)^{\frac{1}{2}} \quad (4)$$

The reduced chi-square (χ^2) was used in the fit test. The square root was the standard error of the regression. The equation with the smallest chi-square value is the best. Chi-square (χ^2) was calculated according to equation (5)

$$\chi^2 = \frac{\sum(MR_{Ex} - MR_{Pred})^2}{N-n} \quad (5)$$

Where χ^2 is the reduced chi-square, n is the number of positive integer parameters and N is the number of observations. The assumptions used in this chi-square test are that both variables are categorical, observations are independent, cells in the contingency table are mutually exclusive, and the number of data is more than 5. This study calculated the moisture ratio from 7 equation models, as shown in Table 3. An assessment was carried out using CurveExpert Professional 2.3.0 software to see the correlation coefficient (R^2) values. After that, further analysis was carried out on the three best equations. Then, a statistical analysis was conducted to obtain the best Root Mean Square Error (RMSE) and Chi-Square (χ^2) values.

Equation (6) shows the value of the moisture ratio as a result of modifying the Fick equation for rectangular, cylindrical, and round materials.

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

Where n is the positive number, D_{eff} is the effective moisture diffusion and L is the half-length of a sample.

The above equation can also be applied to objects like plates such as bagasse, assuming a uniform moisture ratio. For drying over a sufficiently long period, equation (6) can be written as equation (7):

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

Equations 6 and 7 are used to obtain the value of the effective diffusion (D_{eff}). Moisture effective diffusion (D_{eff}) describes the moisture movement rate from the inside of the material to the surface area.

Graphically, the coefficient of effective diffusion is the slope of the curve, which can also be obtained by plotting the ln MR value and drying time [39] and [40]. The D_{eff} value is calculated using the following equation:

$$D_{eff} = \text{slope x } \frac{4L^2}{\pi^2} \quad (8)$$

The error in each experiment is also calculated in this study. This error is calculated to see the difference in results obtained between the equation model and the experimental results. A slight difference indicates that the equation obtained is good. The error that occurs is calculated from equation 9 [41].

$$E(\%) = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{Experimental\ value - Predicted\ value}{Experimental\ value}\right| \quad (9)$$

RESULTS AND DISCUSSION

The equilibrium moisture content in the experiment is obtained when there is a significant change in the sample's mass. The investigation was carried out by varying the drying temperature of bagasse, namely 140, 160, 180, and 200 °C, with the longest time being 46 minutes. The moisture ratio is calculated based on equation 2 for each mass sample. The results of experiments for different sample masses are shown in Figures 2, 3, and 4. There are three stages in drying: constant rate, first-stage falling rate and second-stage falling rate. In this study, constant drying cannot be seen because this stage usually lasts very briefly. From the beginning, the drying that occurs is the first stage falling rate followed by the second stage. At a temperature of 140°C for a mass of 100 gr, the first stage falling rate ends at around minute 20 (Fig. 2). While at 200 °C drying and a mass of 100 gr, the first stage falling rate ends at around minute 12th. After that, the second stage of falling rate occurs until drying is complete or reaches equilibrium. Figures 2, 3 and 4 also show the change in the drying stage from the first-stage falling rate to the second-stage falling rate. The change is faster when the temperature is higher and the mass is smaller. In the first stage falling rate, the drying rate will be controlled by the rate of moisture diffusion from the inside to the object's surface. In the second stage falling rate, the drying rate is controlled by the moisture concentration gradient between the inside and the object's surface [42]. This condition is seen in all Figures 2, 3, and 4 even though it is at different times and in different moisture content. For drying 150 gr and temperature 200 °C (Fig. 4.), this change occurs around the 22nd minute.

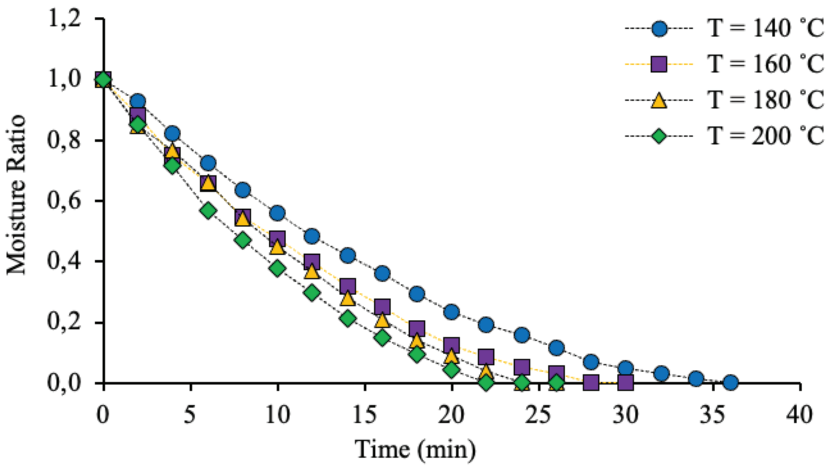

Figure 2. Moisture ratio for 100 gr sample mass at various temperatures.

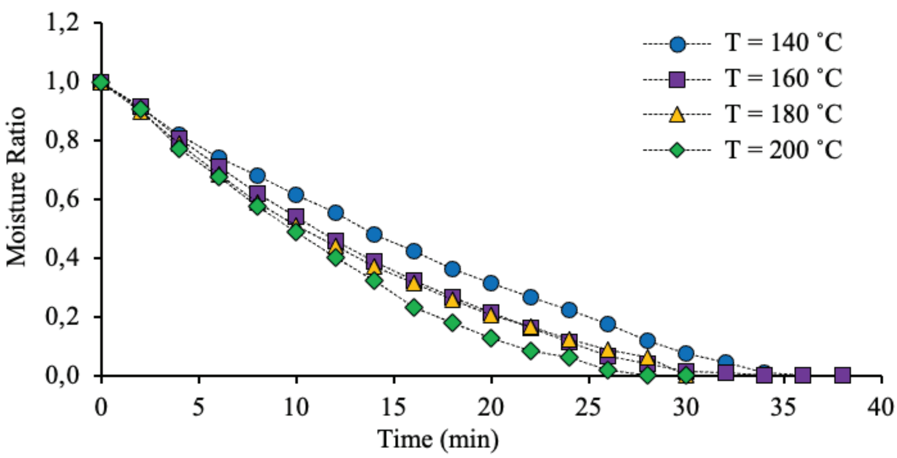

Figure 3. Moisture ratio for 125 gr sample mass at various temperatures.

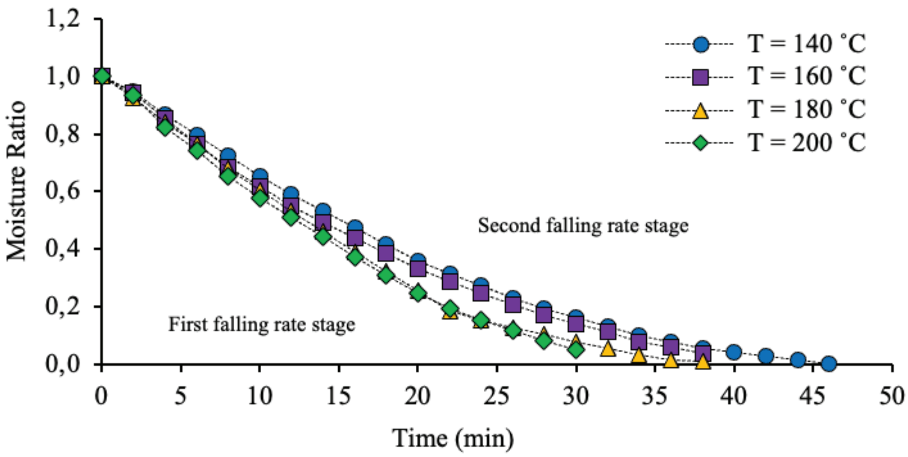

Figure 4. Moisture ratio for 150 gr sample mass at various temperatures.

The three figures show an exponential trend of decreasing moisture ratio. The results showed that the lightest sample mass and the highest temperature required 22 minutes. This sample was the fastest in reaching equilibrium moisture content. The moisture content is decreased rapidly in the first 20 minutes. The graph shows that constant rate drying and falling rate dominate the drying process and last until the end of drying. This condition is the same as in previous studies conducted by Akpinar, 2010 [43] and Simanjuntak et al., 2019 [44]. Figure 2 shows that the moisture ratio approaches zero for temperatures 140, 160, 180, and 200 °C after 36, 28, 24, and 24 minutes of drying, respectively. For temperatures 160 and 180 °C, insignificant differences occur until the 10^{th} minute and then widen until the end of drying. Figure 3 shows that a temperature of 200 °C dries faster than a lower temperature. Temperatures of 160 and 180 °C did not significantly differ in moisture ratio from the beginning to the end of drying. For a temperature of 200 °C, the moisture ratio approaches zero after the sample is dried for 35 minutes. Meanwhile, a temperature of 200 °C will approach zero after 28 minutes.

Figure 4 shows that for temperatures of 140 and 160 °C, the moisture ratio approaching zero takes 38 minutes. For temperatures of 180 and 200 °C, it takes 36 minutes. Temperatures of 140 and 160 °C do not significantly differ in moisture ratio, as do the temperatures of 180 and 200 °C. Figures 2, 3 and 4 show that increasing the sample mass will increase the drying time, especially at lower temperatures. For a temperature of 140 °C, an additional mass of 50 grams or 50% will affect drying time from 22 to 38 minutes or around 58%. It is shown that adding heat is in line with the speed of evaporation of the water mass in the sample.

In constant-rate drying, there is sufficient moisture in the material so that the diffusion rate is controlled by the moisture diffusion from the inside to the surface. In the falling rate section, the drying rate will be affected by the diffusion rate to the surface and in this condition, the amount of moisture is low. In all drying conditions, it can be seen that the highest temperature and the least mass will experience the fastest drying. It occurs because the material absorbs more energy to evaporate the moisture of the material.

The statistical parameters like constant, R^2, RMSE, and (χ^2) values are shown in Tables 3, 4, and 5. These values are important to determine which equation model best suits the experiments carried out in this research. The most suitable equation model is the one that has the R^2 value closest to 1 and the smallest RMSE and chi-square values. The R^2 value is calculated according to equation 3, and then the R-value is found. The results of statistical analysis in those tables show that the Wang and Singh equation model is the most suitable for this study. The coefficient of correlation R was obtained from 0.9987 - 0.9998 or 0.9974 - 0.9996 for R^2 values. The RMSE value is calculated according to equation 4. It is obtained that the smallest RMSE value is 0.00307 in Wang and Singh's drying model for the 160 °C experiment and 150 gr sample mass. This value indicates a slight deviation from the prediction, represented by the equation model and the observation results. These results are also consistent with research conducted by Nurafifah et al. [45].

The chi-square value (χ^2) is calculated based on equation 5. The chi-square value (χ^2) results from a test that measures how the model compares to the observed data. Wang and Singh's model shows the smallest value of χ^2 the most of all types of experiments conducted. Overall, the value of χ^2 ranges from 0.00001 – 0.01290. The small values indicate slight deviations between predictions and experiments.

Of all the experiments conducted, the Wang and Singh equation model was the best because the correlation coefficient value was the closest to 1. Then followed by the Logarithmic equation model and Modified Page. Wang and Singh's Model as the best-fit model was also found by [46] on carrot drying by using a tunnel dryer and [47] on tincalconite drying by using a microwave.

Table 3. The results of statistical analysis at different temperatures for a mass of 100 gr

Temperature (°C)	Model	Constant	R^2	RMSE	Chi-square (χ^2)
140	Wang and Singh	a = -5.224 E-02; b = 6.798 E-04	0.9995	0.00640	0.00005
	Two terms	a = -2.983 E+03; k_1 = 1.000 E+00; b = 2.984 E+03; k_2 = 1.001 E+00	0.9992	0.00830	0.00008
	Verma	a = 8.664 E+00; k = 1.060 E+00; g = 9.314 E-01	0.9992	0.00840	0.00008
160	Wang and Singh	a = -6.262 E-02; b = 9.777 E-04	0.9996	0.00672	0.00005
	Two terms	a = 2.821 E +03; k_1 = 1.007 E +00; b = -2.819 E +03; k_2 = 1.007 E +00	0.9972	0.01255	0.00017
	Verma	a = 1.229 E +0; k = 1.132 E +00; g = 1.049 E +00	0.9969	0.01461	0.00024
180	Wang and Singh	a = -6.512 E- 02; b = 9.845 E- 04	0.9978	0.03915	0.00121
	Two terms	a = -2.203 E +03; k_1 = 9.964 E-01; b = -2.201 E-03 k_2 = 9.957 E-01	0.9963	0.01717	0.00035
	Verma	a = 1.022 E +01; k = 8.933 E- 01; g = 7.589 E- 01	0.9966	0.01726	0.00035
200	Wang and Singh	a = -1.276 E -03; b = 4.011 E -07	0.9993	0.00781	0.00070
	Two terms	a = -1.224 E +05; k_1 = 1.011 E +00; b = 1.224 E +05 k_2 = 1.011 E +00	0.9930	0.02592	0.00780
	Verma	a = 8.894 E +00; = 1.000 E +00 k = 1.013 E +00; g = 8.839 E +01	0.9986	0.01164	0.00016

Table 4. The result of statistical analysis at different temperatures for a mass of 125 gr

Temperature (°C)	Model	Constant	R^2	RMSE	Chi-square (χ^2)
140	Wang and Singh	a = - 4.319 E -02; b = 4.486 E-06	0.9995	0.06770	0.00515
	Two terms	a =-3.308 E +03; k_1= 9.996 E – 0; b = 3.309 E+03; k_2= 1.000 E -00	0.9986	0.06250	0.00400
	Verma	a = 8.989 E +00; k = 9.769 E – 01; g = 9.305 E – 01	0.9984	0.06970	0.00546
160	Wang and Singh	a = -5.357 E -02; b = 7.085 E -04	0.9996	0.05574	0.00352
	Two terms	a = -2.983 E +03; k_1 = 9.991 E – 01; b = 2.984 E +03 k_2 = 9.994 E – 01	0.9983	0.05768	0.00377
	Verma	a = 1.220 E +01; k = 1.026 E +00; g = 9.434 E – 01	0.9974	0.05809	0.00382
180	Wang and Singh	a = -5.395 E -02; b = 6.927 E -04	0.9980	0.01354	0.00210
	Two terms	a = -2.656 E +03; k_1 = 1.000 E +00; b = 2.657 E +03; k_2 = 2.000 E +00	0.9973	0.01429	0.00002
	Verma	a = 1.051 E +01; k = 1.493 E – 01; g = 8.223 E – 01	0.9964	0.01671	0.00032
200	Wang and Singh	a = -6.090 E -02; b = 9.009 E -04	0.9988	0.01049	0.00013
	Two terms	a = 3.711 E +01; k_1 = 2.684 E +00; b = 3.809 E +01 k_2 =2.622 E +00	0.9957	0.02132	0.00052
	Verma	a = 9.100 E +00; k = 9.612 E +01; g = 8.212 E -01	0.9971	0.01636	0.00031

Effective moisture diffusion D_{eff} is important for drying. It shows the amount of moisture that moves through a unit of surface area in a unit of time. The D_{eff} value will be influenced by temperature. Higher temperatures will increase the difference in moisture in the air and the material's surface. In addition, it also causes vapor pressure on the surface of the material. High surface vapor pressure will make moisture more easily diffused into the air. Effective moisture diffusion D_{eff} calculated in this equation is an average value or linearized from the data that occurs during drying.

Effective moisture diffusion (D_{eff}) is calculated based on equation 8. Its value can be obtained by linearizing the value of the moisture ratio. In this study, D_{eff} was obtained from experiments at a temperature of 200 °C with varying masses. The linear relationship between the bagasse drying time and ln (MR) is shown in Figure 5. The effective

Table 5. The result of statistical analysis at different temperatures for a mass of 150 gr

Temperature (°C)	Model	Constant	R^2	RMSE	Chi-square (χ^2)
140	Wang and Singh	a = -3.804 E – 02; b = 3.492 E – 04	0.9974	0.10540	0.01212
	Two terms	a = -3.799 E +03; k_1 = 1.002 E +00; b = 3.800 E +03; k_2 = 1.003 E +00	0.9977	0.10780	0.01268
	Verma	a = 1.225 E + 01; k = 9.447 E – 01; g = 9.399 E – 01	0.9954	0.10430	0.01187
160	Wang and Singh	a = -5.333 E – 02; b = 6.975 E – 04	0.9996	0.25920	0.07250
	Two terms	a = 2.819 E +03; k_1 = 1.000 E +00; b = -2.818 E +03; k_2 = 9.999 E -01	0.9987	0.25982	0.07651
	Verma	a = 1.361 E +01; k = 8.821 E – 01; g = 8.042 E - 01	0.9983	0.25578	0.07415
180	Wang and Singh	a = -4.704 E – 02; b = 5.334 E – 04	0.9981	0.01398	0.00022
	Two terms	a = -3.418 E +03; k_1 = 1.001 E +00; b = 3.149 E +03; k_2 = 1.002 E +00	0.9968	0.01828	0.00037
	Verma	a = 1.090 E +01; k = 9.677 E – 01 g = 8.491 E – 01	0.9965	0.02146	0.00051
200	Wang and Singh	a = -4.807 E – 02; b = 5.456 E – 04	0.9993	0.00932	0.00010
	Two terms	a = 2.820 E +03; k_1 = 9.982 E – 01; b = -2.820 E +03; k_2 = 9.977 E -01	0.9988	0.01041	0.00012
	Verma	a = 1.110 E – 02; k = 9.065 E – 01; g = 7.849 E – 01	0.9983	0.01288	0.00031

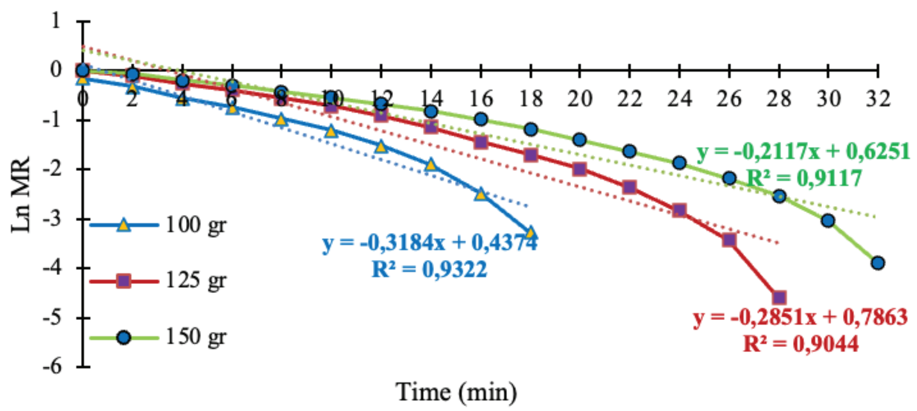

Figure 5. The relationship between drying time and Ln (MR) at T = 200°C.

diffusion values of D_{eff} for each sample mass of 100, 125, and 150 gr for a sample mass of 200 °C were 2.72 x 10^{-5}, 2.60 x 10^{-5}, and 1.93 x 10^{-5} m^2/s. This means that lighter samples will dry more quickly than heavier samples. A significant moisture diffusion effective (D_{eff}) value indicates that moisture leaves the material more quickly and vice versa. The moisture diffusion effective (D_{eff}) value for the 100 gr sample is lower than the others. Bagasse has higher porosity, so moisture diffuses more easily into dry air. The high temperature of the drying air causes moisture to diffuse into the air much more quickly. This value is not much different from the highly porous material reported by Tong dan Lung, 1990 [48] in bread drying. This study reported a D_{eff} value of 2.5×10^{-5} to 5.5×10^{-3} cm^2/s in drying at 20 - 100 °C temperatures. In addition, Kupzack et al., 2018 [49] stated that the effective moisture diffusion in the paper was 2 x 10^{-6} m^2/s measured at a temperature of 24 °C. Paper is also a porous medium and sugar cane fiber can be used as pulp.

A comparison of the moisture ratio between the experiment and the Wang and Singh model for temperatures of 140 and 200 °C is shown in Figures 6 a, b, c and d. Differences can be seen according to data collection from time to time. Generally, there are no significant differences between the types of experiments that were carried out. The average error values that occur can also be seen in Table 6. It shows that the Wang and Singh model is not much different from the experiments carried out.

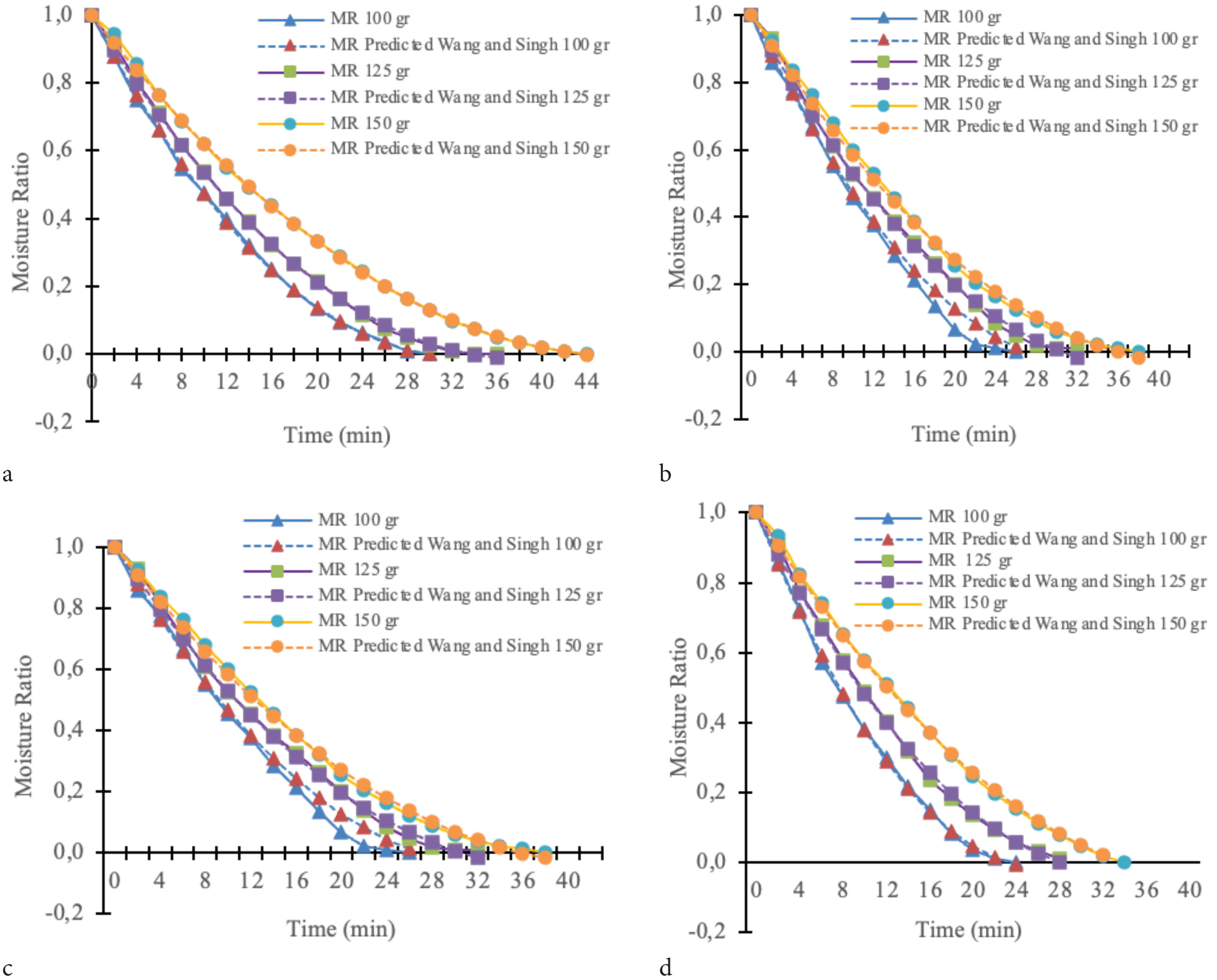

Figure 6. Validity experiment and Wang and Singh model on the temperature of (a). 140 °C, (b). 160 °C, (c). 180 °C and (d). 200 °C.

Error analysis compares experiments and predictions based on the kinetic model used. It will be reflected in RMSE (Root Mean Square Error), where the calculation is based on equation 4. It can also be calculated using equation 9, as researchers did [42]. The error obtained for this method is shown in Table 7, for the most significant error is obtained when the Moisture ratio becomes smaller. It is normal, considering that slight differences in numbers will significantly influence the value received. The value is still low on average. The error values obtained were 4.14, 4.00, and 2.25% for masses of 100, 125, and 150 gr, respectively, for experiments with a temperature of 200 °C. These values are quite small, as are the RMSE values. Generally, the error value is below 5%, which means it is an extremely good fit. The most significant error was obtained in experiments with a temperature of 180 °C. The error values above 10% (poor agreement) were obtained in experiments with masses of 100 and 125 gr. Errors in MR calculations are shown in Table 7.

Table 6. Error analysis (%)

Temp	Sample mass		
	100 gr	**125 gr**	**150 gr**
140 °C	2.6	2.93	3.99
160 °C	4.5	4.75	2.77
180 °C	14.88	13.03	2.05
200 °C	4.14	4.00	2.25

CONCLUSION

This research was carried out to obtain a drying kinetic model for bagasse, moisture effective diffusion, drying stage and error calculation. The samples were dried in a rotary dryer with 3 rpm and temperatures of 140, 160, 180, and 200 °C. The sample masses are 100, 125, and 150 gr with lengths of 3 cm. The sample's moisture content decreased significantly after drying for 35 minutes for all experiments. This research shows that the most suitable drying model is the Wang and Singh model due to the highest correlation coefficient. This model also has low Root Mean Square Error and chi-square (χ^2) values. In this model, the R^2 value is 0.9974 – 0.099969, the RMSE value is 0.00640 – 0.06770. The chi-square value is 0.00005 – 0.07250. The constant drying rate cannot be known because this phase lasts very briefly. The first and second falling rate stages are quite clear and are influenced by the temperature and mass of the sample. The effective moisture diffusion is evaluated at the highest drying air temperature of 200 °C. The D_{eff} values of 100, 125, and 150 gr sample masses are 2.72 x 10^{-5}, 2.60 x 10^{-5} and 1.93 x 10^{-5} m^2/s, respectively. The error between the experimental and the Wang and Singh model was mainly below 5% except at a temperature of 180 °C for sample masses of 100 and 125 gr.

NOMENCLATURE

M_R	moisture ratio
M_b	moisture content on a wet basis, %
M_i	initial moisture content, %
M_{eq}	equilibrium moisture content, %
R^2	the correlation coefficient
MR_{Pred}	the (dimensionless) predicted moisture ratio
MR_{Ex}	experimental (dimensionality) moisture ratio
$\overline{MR_{Prd}}$	average predicted moisture ratio
k	constant
T	time, min
y	constant
a	constant
b	constant
g	constant
k_1	constant
k_2	constant
RMSE	root mean square error
N	number of observations
n	number of parameters that are positive integers.
L	the half-length of material, m
D_{eff}	the moisture effective diffusion, m^2/s

Greek symbols

α	Weibull model scale
β	shape parameter
χ^2	chi-square

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

[1] Badan Pusat Statistik. Sekretariat Direktorat Jenderal Perkebunan. Statistik Perkebunan Indonesia Komoditas Tebu 2017-2019.2018. (In Bahasa).

[2] Salunke VV, Deshmukh KB, Garud RP, Patil AS, Kulkarni SC. Improvement of boiler efficiency using bagasse dryer. Intern Research J Eng Technol 2017;4:1286–1289.

[3] Parvez Y, Hasan MM. Exergy analysis and performance optimization of bagasse fired boiler. Material Sci Eng 2019;69:012089. [CrossRef]

[4] Paturau JM. Alternative uses of sugarcane and its by-product in agroindustry. Available at: https://www.fao.org/4/s8850e/S8850E03.htm. Accessed on Aug 18, 2024.

[5] Simanjuntak ME, Widyawati PS. The effect of microwave mower to sugarcane bagasse drying process. Flywheel 2020;6:20–26. [CrossRef]

[6] Srinivasan V, Nagarajan LA, Mohan C. Drying of bagasse into the fluidized bed vertical dryer using hot air flow through nozzles. Turkish J Comp Mathematic Educ 2018;9:456–473.

[7] Wheatly G, Situ R, Dwyer J, Larsen A, Rubel RI. Dryer design parameters and parts specifications for an industrial scale bagasse drying system. Acta Agronomica 2020;69;4:293–305. [CrossRef]

[8] Camargo JMO, Rios JMG, Neto AMP, Antonio GC, Modesto M, Leite JTC. Characterization of sugarcane straw and bagasse from dry cleaning system of sugarcane for cogeneration system. Renew Energy 2020;158:500–508. [CrossRef]

[9] Khongam T, Salakkam A. Bioconversion of sugarcane bagasse and dry spent yeast to ethanol through a sequential process consisting of solid-state fermentation, hydrolysis, and submerged fermentation. Biochem Eng J 2019;50:1–7. [CrossRef]

[10] Mustafa AM, Li H, Radwan AA, Sheng K, Che X. Effect of hydrothermal and $Ca(OH)_2$ pre-treatments on anaerobic digestion of sugarcane bagasse for biogas production. Bioresource Technol 2018;259:54–60. [CrossRef]
[11] Thomas BS, Yang J, Baharudeen AHM, Nazar S, Jittin V, Ashish DK. Sugarcane bagasse ash as supplementary cementitious material in concrete – a review. Material Today Sustain 2021;15:1–19. [CrossRef]
[12] Sarkar S, Arya A, Gaur UK, Dan GK. Investigations on porous carbon derived from sugarcane bagasse as an electrode material for supercapacitors. Biomass Bioenergy 2020;142:105730. [CrossRef]
[13] Murugan P, Dhanushkodi S, Sudhakar P, Wilson VH. Industrial and small-scale biomass dryers: An overview. Energy Eng 2021;118:435–446. [CrossRef]
[14] Delele MA, Weiglera F, Mellmanna J. Advances in the application of rotary dryer for drying of agricultural products: A review. Dry Technol Intern J Manusc 2015;33:541–558. [CrossRef]
[15] Sai PST. Drying of solids in a rotary dryer. Dry Technol 2013;31:213–223. [CrossRef]
[16] Olalekan ASA. Banana nutrition - Function and Processing Kinetics. London: Intechopen; 2020. p. 114.
[17] Shah S, Joshi M. Modelling microwave drying kinetics of sugarcane bagasse. Intern J Elect Eng 2010;2:159–163.
[18] Szadzińska J, Mierzwa D. The influence of hybrid drying (microwave-convective) on drying kinetics and quality of white mushrooms. Chemical Eng Processing Process Intens 2021;167:108532. [CrossRef]
[19] Kadam SU, Tiwari BK, Donnel CP. Effect of ultrasound pre-treatment on the drying kinetics of brown seaweed Ascophyllum nodosum. Ultrasonic Sonochemi 2015;23:302–307. [CrossRef]
[20] Selvi KC. Investigating the influence of infrared drying method on linden (Tilia platyphyllos Scop.) leaves: Kinetics, color, projected area, modeling, total phenolic, and flavonoid content. Plants 2020;9:916. [CrossRef]
[21] Khaloahmadi A, Roustapour O, Farzaneh B. Mathematical modeling of drying food waste in cabinet dryer with conventional tray. Food Technol Research J 2023;2:75–81. [CrossRef]
[22] Dejchanchaiwong R, Arkasuwan A, Kumar A, Tekasakul P. Mathematical modeling and performance investigation of mixed-mode and indirect solar dryers for natural rubber sheet drying. Energy Sustain Develop 2016;34:44–53. [CrossRef]
[23] Kang SS, Kim JH. Kinetics mechanism and thermodynamics studies of vacuum drying of biomass from taxus chinensis cell culture. Biotechnol Bioprocess Eng 2020;25:336–343. [CrossRef]
[24] Zhang XY, Chen MQ. A comparison of isothermal with nonisothermal drying kinetics of municipal sewage sludge. J Therm Analys Calorimet 2015;123:665–673. [CrossRef]
[25] Nadhari WNAW, Hashim R, Daish M, Sulaiman O, Hiziroglu S. A model of drying kinetics of Acacia mangium wood at different temperatures. Drying Technology 2014;32:361–370. [CrossRef]
[26] Ayuni DQ, Subagio A, Prasetyningrum A, Sasongko SB, Djaeni M. The optimization of paddy drying in the rotary dryer: energy efficiency and product quality aspects analysis. Food Research 2024;8:125–135. [CrossRef]
[27] Simanjuntak M, Widyawati PS. Drying of Sugarcane bagasse in the microwave: Drying kinetics, effective diffusion and energy aspect. J Teknol Hasil Pertanian. 2021;15:262–273. [CrossRef]
[28] Akan AE, Unal F. An application to error and uncertainty analysis in industrial type dryer experiments. Turkish J Eng 2021;5:75–80. [CrossRef]
[29] Chia SL, Chog GH. Effect of rotation speed and steam pressure on physico-chemical properties of drum dried pitaya (Hylocereus polyrhizus) peel. Intern Food Research J 2015;22:372–376.
[30] Singh N, Pratap B, Kamboj SK. Performance evaluation of boiler In 46 MW bagasse-based cogeneration power plant. Intern J App Eng Research 2018;13:149–158.
[31] Shatskikh YV, Sharapov AI, Byankin IG. Analysis of Deep Heat Recovery From Flue Gases. J Phys Conf Ser 2017;891:012188. [CrossRef]
[32] Ismail O, Beyribey B, Doymaz I. Effect on drying characteristic, energy consumption and color nectarine. J Therm Eng 2016;2:801–806. [CrossRef]
[33] Doymaz I, Kipcak AS. Drying characteristic investigation of black mulberry dried via infrared method. J Therm Eng 2019;5:13–21. [CrossRef]
[34] Hagıg KA, Acar B, Dağdeviren A, Taşkesen E. Özkaymak M. Freeze-drying kinetics and diffusion modeling of hawthorn. J Therm Eng 2023;9:876–884. [CrossRef]
[35] Guiné RPF. Fontes L, Lima MJR. Drying kinetics and mass transfer properties in the drying of thistle flower. Braz J Food Technol 2019;22:1–13. [CrossRef]
[36] Sekhar YR, Pandey AK, Mahbubul IM, Avinash GRS, Vekat V, Pochont NR. Experimental study on drying kinetics for zingiber officinale using solar tunnel dryer with thermal energy storage. Solar Energy 2021;15:174–186. [CrossRef]
[37] Resende O, Oliveira DEC, Costa LM, Junior WNF. Drying kinetics of Baru fruit (Dipteryx alata Vogel). Eng Agric 2018;38:103–109. [CrossRef]
[38] Inyang UE, Oboh IO, Etuk BR. Kinetics models for drying technique-food material. Advan Chem Eng Sci 2018;8:27–48. [CrossRef]
[40] Jayatunga GK, Amarasinghe BMWPK. Drying kinetics, quality, and moisture diffusivity of spouted bed dried Sri Lankan black pepper. J Food Eng 2019;263:38–45. [CrossRef]

[41] Ameri B, Boumahdi M, Hanini S. Influence of drying methods on the thermodynamic parameters, effective moisture diffusion and drying rate of wastewater sewage sludge. Renew Energy 2020;147:1107–1119. [CrossRef]

[42] Fernando JAKM, Amarasinghe ADUS. Drying kinetics and mathematical modeling of hot air drying of coconut coir pith. Spring Plus 2016;5:807. [CrossRef]

[43] Mujumdar AS. Handbook of Industrial Drying. 4th ed. Boca Raton: CRC Press; 2014. p. 1348.

[44] Akpinar EK. Drying of mint leaves in a solar dryer and under open sun: modeling, performance analyses. Energy Convers Manag 2010;51:2407–2418. [CrossRef]

[45] Simanjuntak ME, Prabowo, Widodo WA, Sutrisno, Sitorus MBH. Experimental and numerical study of coal swirl fluidized bed drying on 10^0 angle of guide vane. J Mechanic Sci Technol 2019;33:5499–5505. [CrossRef]

[46] Nurafifah F, Chuah AL, Wahida MAPF. Drying of Plectranthus amboinicus (lour) spring leaves by using oven dryer. Environ Food 2018;11:239–244. [CrossRef]

[47] Turkan B, Etemoglu AB. Simulation of shrinkage effect in drying of food product in hot air dryer. Sigma J Eng Nat Sci 2020;38:527–544.

[48] Coban S, Ozkarasu B, Senberber FT, Kipcak AS, Doymaz I, Derun EM. Microwave dehydration modelling of tincalconite. J Therm Eng 2018;4:1803–1812. [CrossRef]

[49] Tong CH, Lund DB. Effective moisture diffusivity in porous materials as a function of temperature and moisture content. Biotechnol Prog 1990;6:67–75. [CrossRef]

[50] Kupczak A, Bratasz L, Czerwenka JK, Kozłowski R. Moisture sorption and diffusion in historical cellulose-based materials. Cellulose 2018;25:2873–2884. [CrossRef]