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CHEMICAL ENGINEERING | RESEARCH ARTICLE

Energy–exergy analysis and mathematical modeling of cassava starch drying using a hybrid solar dryer

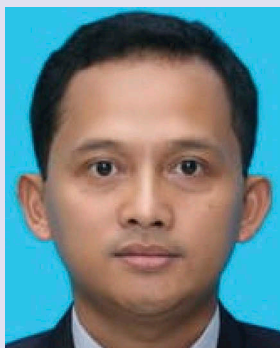
Suherman Suherman^{1*}, Evan Eduard Susanto¹, Asif Widodo Zardani¹,
Nur Haniza Roviqoh Dewi¹ and H. Hadiyanto^{1,2}

Abstract: In this study, we aimed to energetically and exergetically evaluate the usage of a hybrid solar dryer system for cassava drying via a series of drying experiments. The experiments were performed beginning at 10.00 A.M. (hereafter, in local time) until the moisture content of cassava starch became constant at a value less than 14% on a wet basis at drying temperatures of 40 °C to 60 °C and drying times of 180–240 min. The results demonstrated that the highest overall dryer energetic efficiency was 20.82%, which was achieved at a drying temperature at 60 °C, and that the maximum energetic efficiency of 27% was recorded at 11.00 A.M. The exergy flows fluctuated during the drying process and were dependent on the solar radiation and drying conditions; however, the exergetic efficiency of the dryer was 25.1%–73.8%. Comparison of the fitting models denoted that the Page model was the most suitable model for describing the experimental drying performances. The calculated effective diffusivity constant (D_{eff}) and the activation energy (E_a) during the drying process from 50 °C to 60 °C were 3×10^{-10} m²/s and 15.3 kJ/mole, respectively.

Subjects: Industrial Chemistry; Chemical Processing & Design; Drying Technology

Keywords: hybrid solar dryer; cassava starch; energy; exergy; mathematical modeling

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PUBLIC INTEREST STATEMENT

Drying technology is aimed to improve the quality of agricultural products in order to increase the shelf life. In some particular products, the water content should be lowered to deactivate the microbial activity. Solar drying technology is ideally applied in tropical countries, areas that receive excessive sunlight intensity most of the year. In solar drying, solar energy is used as the main source of energy drying. Solar drying technology is very suitable for drying agricultural products, because the drying will not extremely reduce the water contents in the products. With low investment and operating costs, easy operation, solar dryer is the right choice for SME in Indonesia. Solar dryer can be used to dry food and agricultural products such as coffee beans, paddy, cassava starch, corn, onions, etc. In order to anticipate the erratic weather such as clouds and rain, hybrid dryer technology has been developed, which is to add additional energy sources from LPG gas, biomass, etc.

1. Introduction

Cassava is the primary staple food source in Indonesia and can be processed to obtain several products, including cassava starch. With an annual production of 19,046 million tons, Indonesia was the fourth largest producer of cassava starch in 2017 (FAO, 2017). Recently, the demand for cassava starch in Indonesia has increased, especially from the food, textile, chemical, and oil industries, which are heavily dependent on cassava starch (Aviara et al., 2014; Bo & Tunde-Akintunde, 2013). To produce cassava starch, cassava roots are washed, peeled, cut into small pieces, and milled to obtain a starch slurry. Prior to the dehydration process, the pulp and fine fibers must be removed via the extraction and separation processes. The slurry is then dewatered, dried, packaged, and distributed to consumers (Aichayawanich et al., 2011). Moorthy et al. (2018) stated that appropriate drying of cassava starch will prolong its shelf life and retain its quality. Furthermore, the maximum allowable moisture content of the cassava starch products sold in Indonesia is 14% (w.b), as dictated by the Indonesian Standardization Body (2011). Because cassava starch is extracted from an aqueous material, drying is a fundamental operation in cassava starch processing (Aviara et al., 2014).

The most common starch drying method is open sun drying, where the starch is left to dry under the sun and spread in a thin layer. Although this is the cheapest method and does not require additional energy, it is heavily dependent on the weather, requires a long drying time, has a relatively low drying rate, and is prone to outside interferences (e.g., insects, wind, or dust) (Dairo et al., 2015). Among the several drying technologies that have been developed to address these issues, solar dryers are cheap and can be used in many places because they do not require a secondary energy source (Strøm, 2011).

Several studies regarding the drying of cassava starch using various methods have been published. Aviara et al. (2014) conducted the energy and exergy analysis of cassava starch dried using a tray dryer. They observed that increasing the drying temperatures from 40 °C to 60 °C will reduce the drying time from 480 min to 240 min and the final moisture content from 7.1% to 1.7% on a wet basis. The energy and exergy efficiencies also increased with increasing temperature (from 16% to 30.6% and from 13.8% to 20.6%, respectively). Suherman et al. (2015) experimentally studied cassava starch drying using a pneumatic dryer. They observed that when drying at temperatures from 40 °C to 80 °C, the final moisture content decreased from 24% to 5.1% on a wet basis and the drying efficiency increased from 43% to 57%. Suherman and Trisnaningtyas (2015) investigated the thin-layer drying of cassava starch using a continuous-vibration fluidized bed dryer at 50 °C to 70 °C. They observed that over a period of three hours, drying at 70 °C resulted in the fastest moisture reduction (from 21% to 8% on a wet basis). They also discovered that the Page model is the most suitable model to describe the drying kinetics of cassava starch.

However, only some researchers have investigated the use of solar dryers for drying cassava starch. Coriolano et al. (2017) reported that a box-shaped solar dryer could reduce the moisture content of cassava starch from 80% to 10% on a wet basis after five hours of drying, whereas Suherman et al. (2018) reported that the moisture content in cassava starch could be reduced from 54% to 7% on a wet basis after 16 h when using a solar tray dryer.

An additional heat source can be incorporated into a solar dryer to reduce the dependency of the drying process on solar radiation; such a solar dryer is commonly referred to as a hybrid solar dryer. The incorporation of an energy source that is not dependent on the weather (e.g., biomass, electricity, or liquefied petroleum gas) allows a continuous process that can be performed during bad weather or at night (Gudiño-Ayala & Calderón-Topete, 2014). Several researchers investigating the application of hybrid solar dryers on various crops, such as mushrooms (Reyes et al., 2014), chamomile (Amer et al., 2018), mint (Eltawil et al., 2018), and maize (Bosomtwe et al., 2019), have

observed that the usage of a hybrid solar dryer improves the drying process when compared with a normal solar dryer.

Energy analyses are commonly used to assess the performance of a dryer because drying is an energy-intensive process (Aviara et al., 2014). Exergy, or the maximum shaft work that can be conducted using a composite of the system and a specific reference environment, is also a useful performance assessment indicator. Exergy analysis can be used to identify the cause, location, and magnitude of process inefficiencies. Furthermore, because exergy analysis can be used to assess the quality and degradation of energy, it can be used as a tool to decide whether a task is worth performing (Dincer & Rosen, 2007).

Many researchers have performed exergy analyses of the drying processes. For example, Fudholi et al. (2014) observed an average exergy efficiency of 30% via their analysis of solar drying of red seaweed while reducing the moisture content from 90% to 10% on a wet basis. During their exergy analysis of industrial fluidized-bed paddy drying, Sarker et al. (2015) observed that only 31%–37% of the exergy was utilized for drying; additionally, the exergy efficiency decreased with increasing drying temperature.

Among the mathematical modeling approaches that have been used to analyze the drying process, thin-layer models are most commonly used to understand the drying behavior of certain products. The thin-layer models can be used to uniformly explain the drying process, regardless of the controlling mechanism. Several thin-layer drying models, such as the Page, two-term, and Midilli models, have been used to predict the drying behavior of plants (Alara et al., 2019). Charmongkolpradit and Luampon (2017) observed that the Midilli model was in good agreement with their experimental data obtained when drying cassava pulp. Similarly, when studying the thin-layer drying kinetics of pre-gelatinized starch under microwave, Jiang et al. (2017) found the Midilli model to be the best model among the ten drying models that were studied.

However, an extensive literature review has found no works studying the application of a hybrid solar dryer for drying cassava starch and performing an exergy analysis or mathematical modeling of cassava starch drying. Therefore, we aim to study the performance of a hybrid solar cassava starch dryer using liquefied petroleum gas (LPG) as an auxiliary energy source by analyzing the moisture content as well as the energetic and exergetic flows.

2. Materials and methods

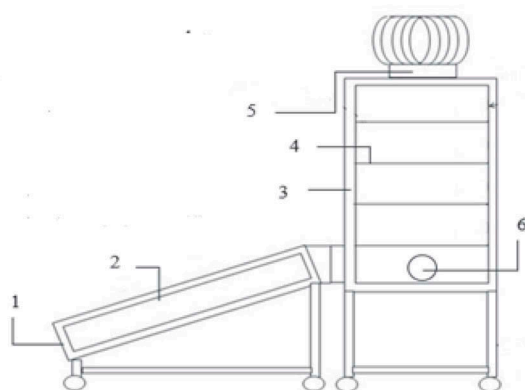
2.1. Materials

Wet cassava starch was obtained from the Cassava Starch Small-Medium Enterprise located at Pati, Central Java, Indonesia. The wet cassava starches were kept in closed plastic jars and stored in a freezer at a temperature of 4 °C to 5 °C. An appropriate amount of wet cassava starch was taken from the freezer two hours prior to the drying experiment (08:00 A.M.) and left open at a room temperature of approximately 26 °C to 28 °C to stabilize their temperatures. An initial moisture content test, performed using the oven method as dictated by the Official Methods of Analysis (Nielsen, 2010), indicated that the initial moisture content of the starch was 39.93% on a wet basis.

2.2. Methods

The hybrid solar dryer used in this study comprised a drying chamber and a solar collector unit and is shown in Figure 1. The drying chamber contained three perforated drying trays, the edges of which were covered with aluminum. The frame of the drying chamber was covered with aluminum for achieving strength and improved conductivity. An exhaust duct was fitted to the top of the drying chamber to allow the air to exit the drying chamber. The frame of the solar collector was covered with aluminum, and a black sheet obtained using thermoplastic rubber was used as the radiation absorber. Nine holes were made in the bottom of the solar collector to allow ambient air

Figure 1. Sketch of a hybrid solar dryer.



Details:

1. Ambient air inlet
2. Solar collector
3. Drying chamber
4. Drying tray
5. Drying air outlet
6. Air pipe connected to the hot air outlet from the burner and blower unit

to flow through the collector and into the drying chamber. Further details about the drying chamber and solar collector are presented in Tables 1 and 2, respectively.

The blower and burner units are shown in Figure 2. The blower sucked ambient air into the drying chamber through a pipe that connected the burner unit and the drying chamber, where air was heated using the flue gas from the LPG burner. The blower–burner system was controlled via a control panel, which also served as a temperature indicator.

A digital scale was used to measure the weight of the cassava starch. The temperature and relative humidity were measured using a Krisbow relative humidity (RH) meter (S000052505). Three 100-g samples of wet cassava starch were prepared at the studied drying temperatures (40 °C, 50 °C, and 60 °C). The blower–burner unit was turned on, and the amount of LPG gas burned was adjusted to ensure that the burner will reach the desired drying temperature. After the burner reached the desired temperature, the samples were placed on three trays inside the drying chamber. The samples were then dried, starting from 10.00 A.M. until the moisture content on each tray became lower than the standard limit, which is 14% on a wet basis. The temperature, RH, solar intensity, and weight of the cassava starch with respect to each tray were measured after every 30 min. The temperature and RH at the inlet (underneath the first tray), outlet (at the

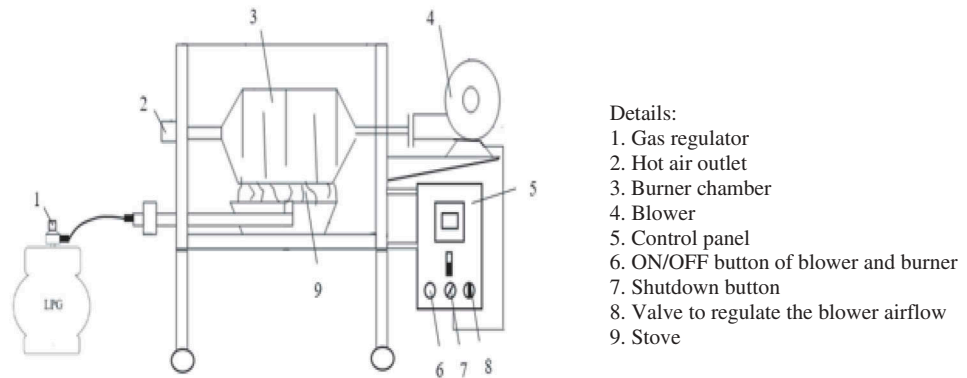
Table 1. Technical details of the drying chamber

No.	Parts	Material	Specification/Information
1.	Drying chamber	Glass and aluminum	100 × 60 × 94 cm (length × width × height)
2.	Tray	Aluminum	56 × 45 cm
3.	Air outlet	Aluminum	36 cm diameter, 40 cm height
4.	Buffer	Iron	101 × 61 × 52 cm
5.	Thermocouple		±0.5 accuracy

Table 2. Technical details of the solar collector

No.	Parts	Material	Specification/Information
1.	Solar collector	Glass and aluminum	100 × 100 × 10 cm (length × width × height)
2.	Solar absorber	Aluminum sheet	Black-painted, placed at the inner bottom of the collector
3.	Outer frame	Aluminum	1-mm thickness
4.	Bottom front of the collector	Wood	Nine air holes were made; each hole had a 6-cm diameter

Figure 2. Sketch of the blower–burner system.



exhaust), each tray in the drying chamber, and ambient were measured. The solar intensity was measured with respect to the solar collector. The drying experiments were performed in triplicate for every drying temperature variable.

2.3. Data analysis

2.3.1. Moisture content analysis

The moisture content of cassava starch was determined by weighing the starch after every 30 min and then using Equation (1) (Dhanushkodi et al., 2014).

$$X = \frac{m_i m_d}{m_i} \tag{1}$$

where X represents the moisture content on a wet basis, m_i is the mass of cassava starch at the time of measurement, and m_d is the mass of dry cassava starch. The moisture content data were obtained thrice, and their average was considered.

2.3.2. Energy analysis

The weight of cassava and solar intensity data were used to determine the energy efficiency of the process (Dhanushkodi et al., 2014).

$$\eta_d = \frac{m_w \cdot h_{fg}}{I \cdot A \cdot t + E + m_{fuel} \cdot C_v} \tag{2}$$

where η_d is the energy efficiency, m_w is the mass of the evaporated water (kg), h_{fg} is the latent heat associated with the vaporization of water (kJ/kg), I is the solar intensity (kW/m^2), A is the area of the solar collector (m^2), t is the drying time (s), E is the energy consumption of the blower (kJ), m_{fuel} is the mass of used fuel (kg), and c_v is the heating value of LPG (kJ/kg).

2.3.3. Exergy analysis

To determine the exergy efficiency (Ex_{eff}), the exergy at the drying chamber inlet (Ex_{in}), the exergy at the drying chamber outlet (Ex_{out}), and the exergy loss (Ex_{loss}) were calculated (Sarker et al., 2015).

$$Ex_{in} = m_{da} \cdot Cp_{da} \cdot \left[(T_{in} - T_{\infty}) - T_{\infty} \cdot \ln \left(\frac{T_{in}}{T_{\infty}} \right) \right] \tag{3}$$

$$Ex_{out} = m_{da} \cdot Cp_{da} \cdot \left[(T_{out} - T_{\infty}) - T_{\infty} \cdot \ln \left(\frac{T_{out}}{T_{\infty}} \right) \right] \tag{4}$$

$$EX_{loss} = EX_{in} - EX_{out}, \tag{5}$$

$$EX_{eff} = \frac{EX_{in}EX_{loss}}{EX_{in}}, \tag{6}$$

where m_{da} is the mass flow of drying air (kg/s), Cp_{da} is the specific heat of drying air (kJ/kg.K), T_{in} is the temperature at the dryer chamber inlet, T_{out} is the temperature at the dryer chamber outlet, and T_{∞} is the ambient temperature.

2.3.4. Mathematical modeling

Seven thin-layer models were used in this experiment; the considered parameters are presented in Table 3.

The modeling was performed using MATLAB software. The moisture ratio (MR) was defined as follows:

$$MR = \frac{M - M_e}{M_o - M_e}, \tag{7}$$

where M is the moisture content at a certain time, M_o is the initial moisture content, and M_e is the equilibrium moisture content. Because the RH of the drying air varied continuously during drying and M_e was relatively small compared to M or M_o , M_e was assumed to be negligible (Dairo et al., 2015; Sanni & Odugogbe, 2016). The root mean square error (RMSE) and the determination coefficient (R^2) were calculated using Microsoft Excel to determine the accuracy of the models as shown in Equations (8) and (9) (Dhanushkodi et al., 2017). A model was determined to be suitable to describe the cassava starch’s drying behavior if the model has a high R^2 value and a low RMSE value.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}, \tag{8}$$

$$R^2 = \frac{\left[\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})(MR_{pre,i} - MR_{pre,i}) \right]^2}{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2 \sum_{i=1}^N (MR_{pre,i} - MR_{pre,i})^2} \tag{9}$$

where Mr_{exp} is the experimental MR, Mr_{pre} is the predicted MR, and N is the number of observations.

Because cassava starch drying mostly occurred in the falling rate period (Tsotsas & Mujumdar, 2011), the drying characteristics were determined using Fick’s diffusion. By assuming a spherical coordinate, uniform initial moisture content distribution, and a long drying time, the relation between MR and effective diffusivity can be expressed as follows (Khama et al., 2016):

Table 3. Thin-layer drying models

No	Model	Formula	References
1	Newton	$MR = \exp(-kt)$	Ayensu (1997)
2	Page	$MR = \exp(-kt^n)$	Menges and Ertekin (2006)
3	Modified Page	$MR = \exp(-kt)^n$	Vega et al. (2007)
4	Henderson and Pabis	$MR = a \cdot \exp(-kt)$	Kashaninejad et al. (2007)
5	Logarithmic	$MR = a \cdot \exp(-kt) + b$	Rayaguru and Routray (2012)
6	Wang and Singh	$MR = 1 + at + bt^2$	Omolola et al. (2014)
7	Midilli	$MR = \exp(-kt^n) + bt$	Midilli et al. (2002)

*k, n, a, b, c: model parameters.

$$MR = \frac{6}{\pi^2} \cdot \exp \left[-\frac{D_{eff} \pi^2}{r^2} \cdot \theta \right], \tag{10}$$

where D_{eff} is the effective diffusivity (m^2/s), r is the radius of the paddy (m), and θ is the drying time (s). By changing Equation (10) into a logarithmic form, a new linear equation is obtained as follows:

$$\ln MR = \ln \left[\frac{6}{\pi^2} \right] - \frac{D_{eff} \pi^2}{r^2} \theta \tag{11}$$

The effective diffusivity (D_{eff}) was determined by calculating the slope of the plot of the natural logarithm of the MR versus the drying time (θ) using Equation (11). The relation between the effective diffusivity and drying temperature can be illustrated using Arrhenius equation, as shown in Equation (12) (Shen et al., 2011).

$$D_{eff} = D_o \exp \left[-\frac{E_a}{RT} \right], \tag{12}$$

where D_o is the diffusivity constant at an infinite drying temperature (m^2/s), R is the universal gas constant (8.314 J/mole.K), E_a is the activation energy (kJ/mole), and T is the absolute temperature (K). E_a and D_o were determined by plotting $\ln D_{eff}$ and $1/T$, as shown in Equation (13).

$$\ln(D_{eff}) = \ln(D_o) - \frac{E_a}{RT} \tag{13}$$

3. Results and discussion

3.1. Weather conditions and temperature profiles in a hybrid solar dryer

Figures 3–5 denote the average solar radiation, ambient temperature, and RH during hybrid solar drying at 40 °C, 50 °C, and 60 °C, respectively. During the experiments, the weather conditions were sunny and slightly cloudy. Figures 6–8 show the temperature profiles with respect to the hybrid solar dryer at 40 °C, 50 °C, and 60 °C, respectively, representing the temperature at the collector inlet and outlet as well as the temperature at the drying chamber inlet and outlet. The collector inlet temperatures on the three days of the experiments were similar, ranging from 27.56 °C to 32.21 °C. The collector outlet temperatures ranged from 38.13 °C to 40.22 °C. The fluctuations of the collector inlet and outlet temperatures are considerably influenced by solar radiation, which also changes over time (Figures 3–5). It is also evident from Figures 6–8 that the dryer outlet

Figure 3. Average weather conditions during hybrid solar drying at 40 °C.

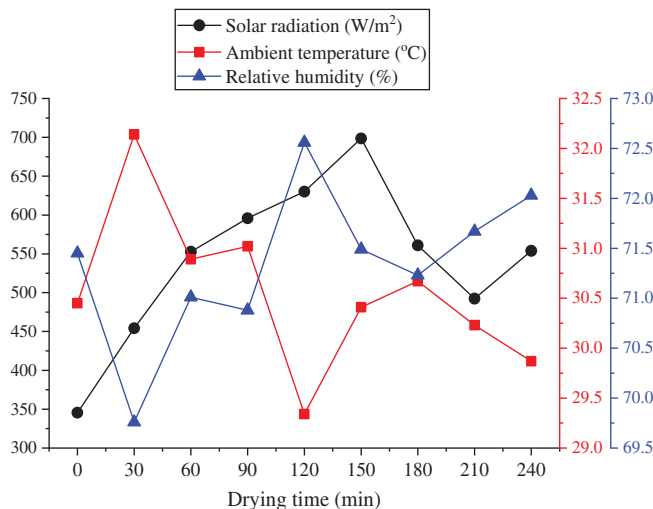


Figure 4. Average weather conditions during hybrid solar drying at 50 °C.

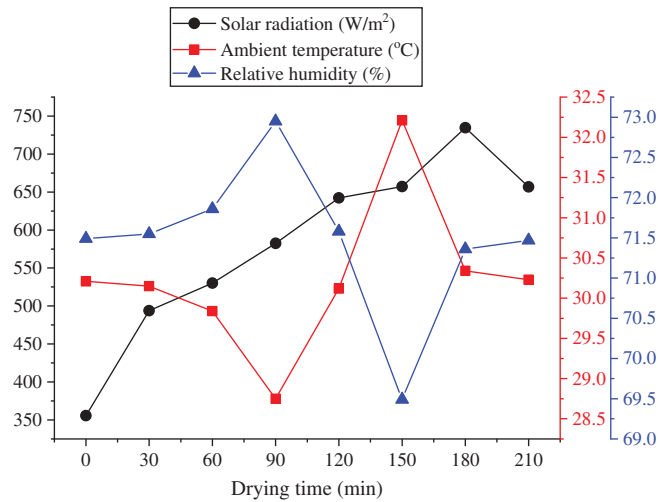
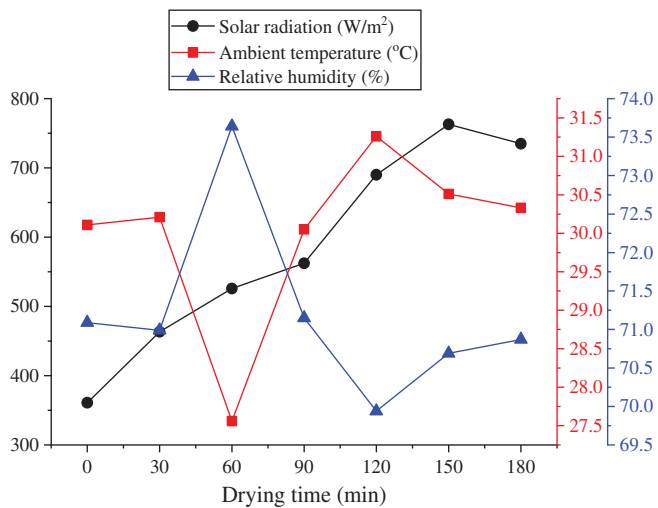


Figure 5. Average weather conditions during hybrid solar drying at 60 °C.



temperatures were lower than the dryer inlet temperatures, with the largest temperature difference being observed during hybrid solar drying at 60 °C. This proves the occurrence of the drying process, and the drying at 60 °C is considered to be the fastest because of the high temperature difference, indicating that a considerable amount of heat is required to evaporate the water from cassava starch (Dhanushkodi et al., 2014; Rathore & Panwar, 2011)

3.2. Moisture content

The resulting moisture content of the cassava starch over time at each studied temperature is shown in Figure 9, from which it can be clearly observed that a higher drying temperature caused the increasingly rapid reduction of moisture. The final moisture contents (on a wet basis) of cassava starch during drying at 40 °C, 50 °C, and 60 °C were 12.69%, 12.81%, and 13.07% at drying times of 240 min, 210 min, and 180 min, respectively. As noted in Section 3.1, drying at 60 °C was the fastest step to achieve the safe moisture content (14% wet basis) established by the Indonesian Standardization Body (2011). At higher temperatures, there is less humidity in the air, allowing more water to be removed from the starch more quickly (Tsotsas & Mujumdar, 2011). This is in agreement with the studies on hybrid solar dryer use performed by Dhanushkodi et al. (2014) with respect to cashew drying and Eltawil et al. (2018) with respect to mint drying.

Figure 6. Temperature profiles during hybrid solar drying at 40 °C.

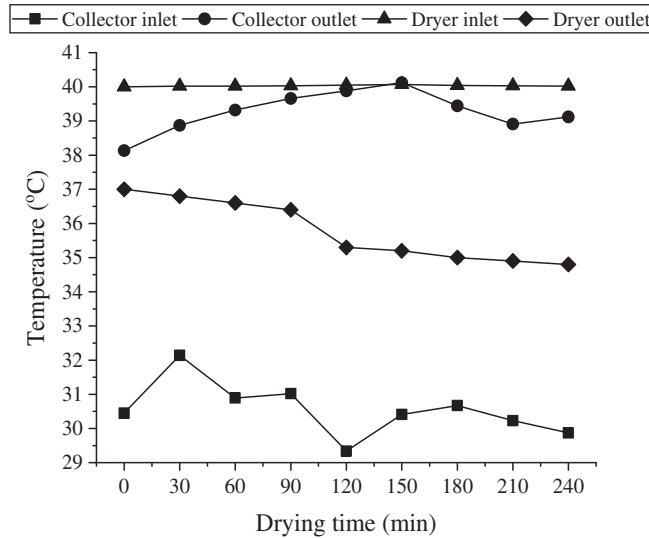
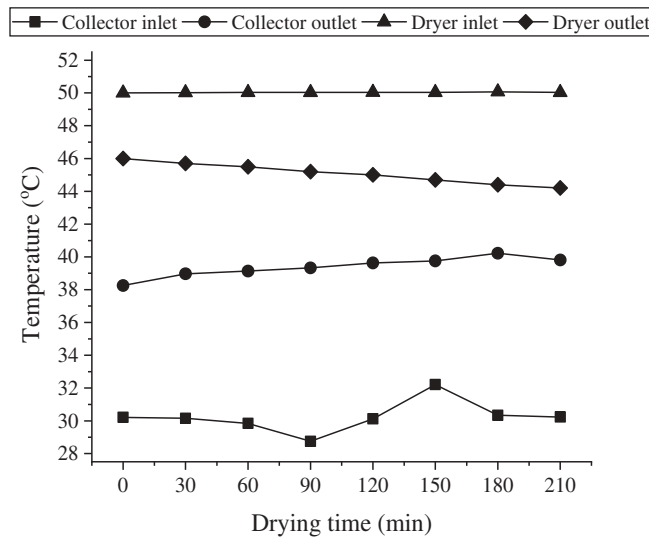


Figure 7. Temperature profiles during hybrid solar drying at 50 °C.



3.3. Energy analysis

As defined in Equation (2), the solar dryer efficiency was calculated as the energy required to evaporate water divided by the total energy consumed by the dryer. The resulting efficiency of each tray drying at 60 °C as a function of time is shown in Figure 10. The drying efficiency fluctuated with the drying time, reaching a maximum of 27% at 11:30 AM on the third tray. Several factors, such as weather conditions and time, influence the efficiency, affecting the solar radiation (Baniyadi et al., 2017). Similar phenomena were observed by Baniyadi et al. (2017) and Reyes et al. (2014), who reported a maximum hybrid solar dryer efficiency from 11.00 A.M. until 12.00 P.M. The overall drying efficiencies of the cassava root on the first tray at drying temperatures of 40 °C, 50 °C, and 60 °C were 19.12%, 19.54%, and 20.82%, as shown in Figure 11 Thus, increased temperature resulted in a slightly higher dryer efficiency. Even though this is in agreement with the study of Aviara et al. (2014), who observed that the dryer efficiency increased from 16% to 30.6% when the temperature increased from 40 °C to 60 °C, the magnitude was observed to differ. More energy will be generated with the increasing drying temperature, accelerating the

Figure 8. Temperature profiles during hybrid solar drying at 60 °C.

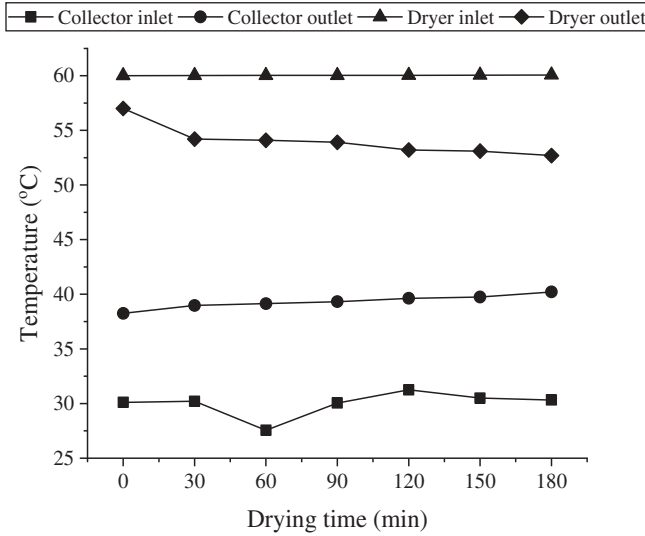
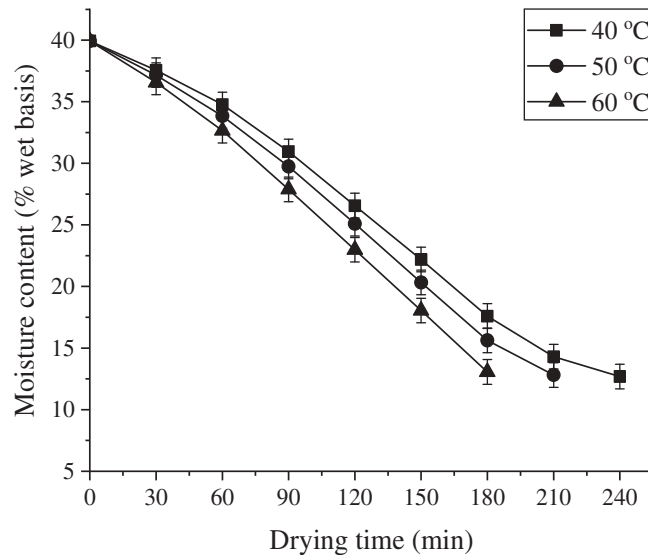


Figure 9. Experimental moisture content versus time curve at different drying temperatures.



heat and mass transfer between the drying air and the water inside the cassava starch as well as increasing the efficiency of the drying process (Safrizal et al., 2012; Suherman & Hidayati, 2018).

3.4. Exergy analysis

Because the exergy represents the maximum amount of work that can be achieved using a stream of matter in a specific reference environment, exergy analysis is an effective method to identify efficiencies that always measure the approach to ideal, revealing the extent of improvement that can be achieved by reducing the inefficiencies in the current system. Further, it can be used to combine and apply the conservation of mass and conservation of energy principles along with the Second Law of Thermodynamics for designing and analyzing energy systems (Dincer & Rosen, 2007).

The overall exergy inflow, outflow, and losses are shown in Figure 12; the three types of exergy flows increased with increasing drying temperatures. A similar phenomenon was observed by Yogendrasasidhar and Setty (2018) regarding the drying of Kodo millet grains and Fenugreek

Figure 10. Drying efficiency versus drying time at 60 °C.

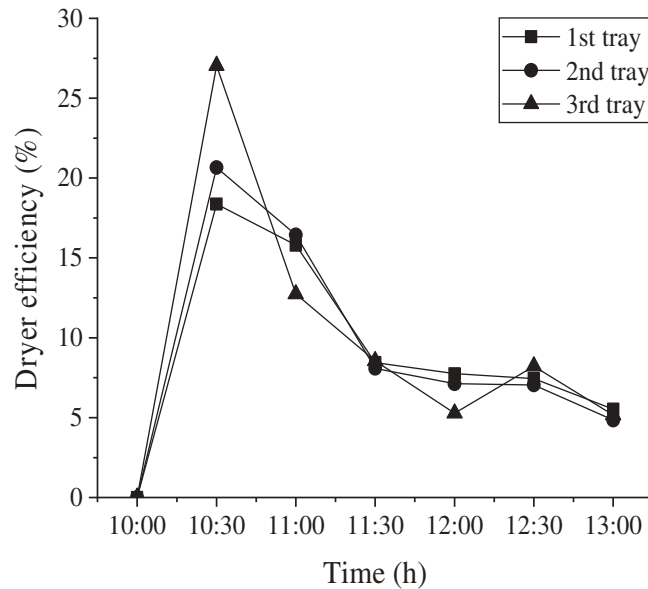
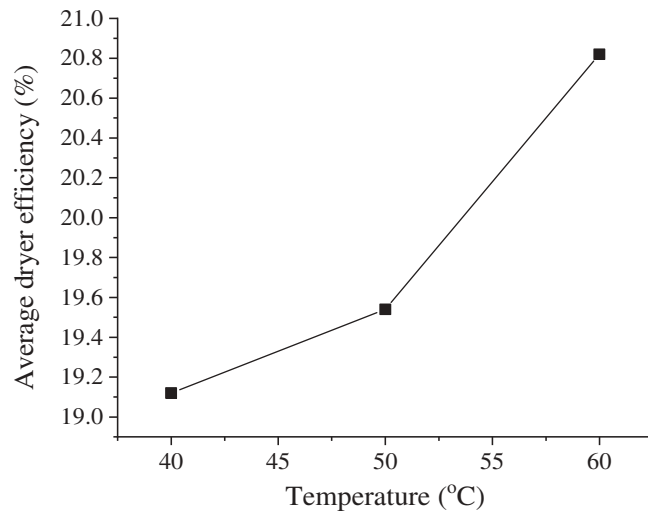


Figure 11. Average drying efficiency at different drying temperatures.



seed, Aviara et al. (2014) regarding cassava starch in a tray dryer, and Beigi et al. (2017) regarding drying rough rice in a convective dryer. The high temperature accelerates the mass and heat transfer, increasing the overall heat transfer coefficient and the exergy flows of the drying systems (Yogendrasidhar & Setty, 2018). According to Beigi et al. (2017), the accelerated mass and heat transfer rates due to increased temperature will augment the exergy destruction rate, which represents the exergy loss, or the losses in the quality and efficacy of the input energy.

The resulting exergy inflow, outflow, and losses when drying at 60 °C as a function of drying time are shown in Figure 13. The exergy flows fluctuated during the drying process, with similar trends being observed with respect to the inflows and outflows. The exergy flow fluctuations can be attributed to the dependence on solar radiation, which varies with time (Karthikeyan & Murugavelh, 2018). The highest exergy inflow and outflow were recorded during the initial phase of drying, which can be attributed to the high temperature difference at this time (Sarker et al., 2015).

Figure 12. Overall exergy inflow, outflow, and loss during cassava starch drying at different temperatures.

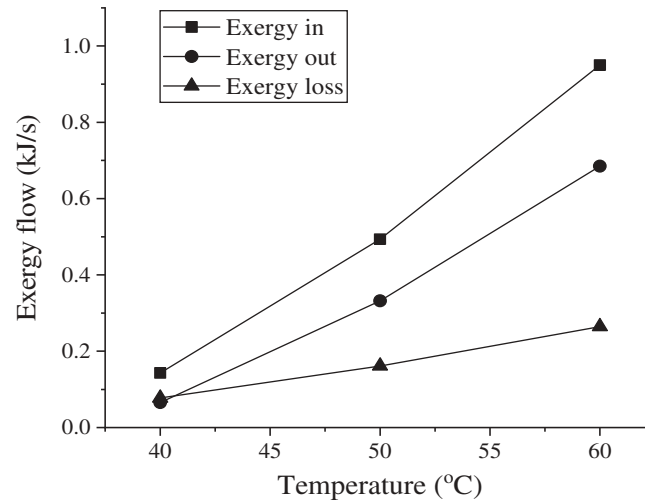
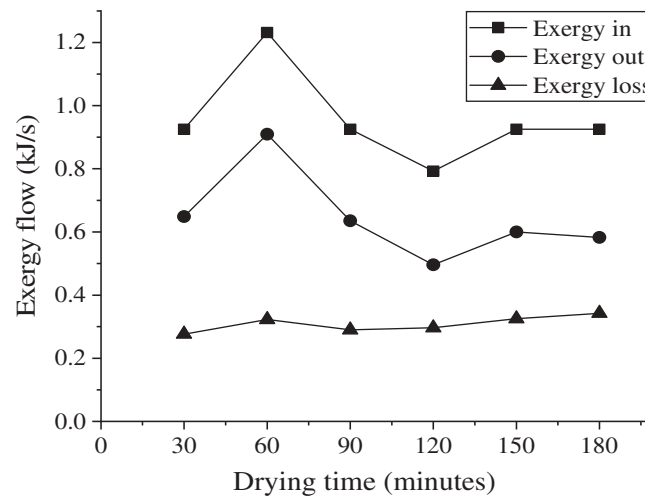


Figure 13. Exergy inflow, outflow, and loss versus time during cassava starch drying at 60 °C.



The overall exergy efficiency at each studied drying temperature is shown in Figure 14 and ranged from 25.1% to 73.8%, which is lower than those found by Rabha et al. (2017) in their work regarding drying of chili pepper and ginger using a solar tunnel dryer (21%–83%) and Fudholi et al. (2014) regarding a solar drying system for reed seaweed (19%–94%). Higher drying temperatures lead to greater exergy efficiency. This occurs because the exergy input will increase, accelerating the moisture evaporation rate. Subsequently, the quantity of exergy input will increase, and the main portion of exergy input is vented by the outlet air without causing any water to evaporate (Beigi et al., 2017).

3.5. Model simulation

Figures 15 and 16 show the cassava starch before and after being dried using a hybrid solar dryer at 60 °C. The cassava starch is uniformly spread and does not shrink during the drying process. The obtained experimental MRs were input into the seven models shown in Table 3 to determine the applicability of these drying models on the drying behavior of cassava starch. The resulting R^2 and RMSE values are presented in Table 4. The RMSE and R^2 values were found to differ randomly and not follow a specific pattern. By taking the average value of the R^2 and RMSE of each model, the Page model was determined to be the most suitable model to describe the drying behavior of cassava starch using a solar tray dryer, followed by the Midilli and Modified Page models. This

Figure 14. Exergy efficiencies with respect to the cassava starch drying process at different temperatures.

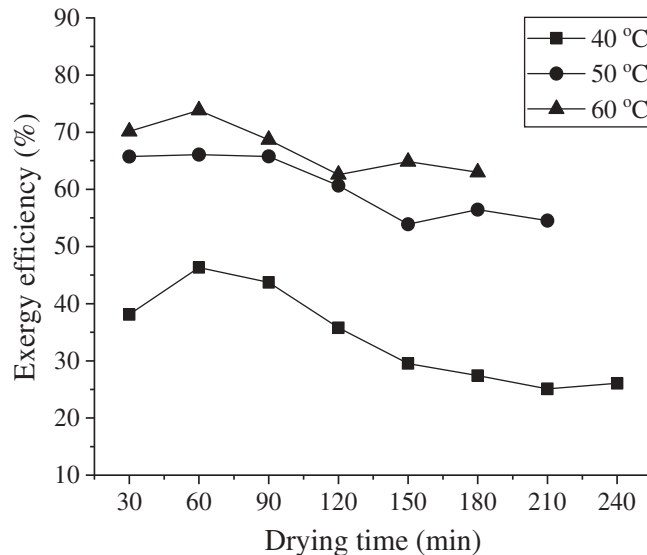
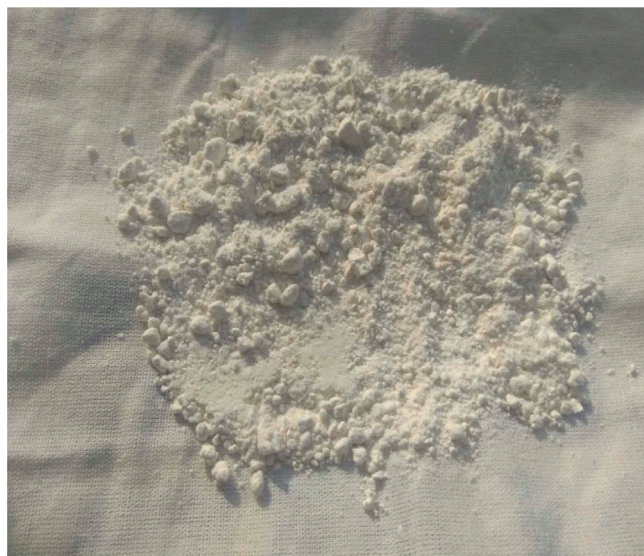


Figure 15. Cassava starch before drying.



differs from the thin-layer models of cassava pulp drying using an oven dryer by Charmongkolpradit and Luampon (2017) and a tray dryer by Aviara and Igbeka (2016), who found that the Midilli model and the Modified Hii et al. model were the most accurate, respectively. These differences may be attributed to the different drying conditions. Based on the comparison of the experimental and simulated drying curves using the Page model at 60 °C, as shown in Figure 17, the simulated MR was observed to gather around the experimental data (represented by a straight line), indicating that the Page model was suitable to describe the drying behavior of cassava starch using a hybrid solar dryer (Koua et al., 2009).

The migration of water from the interior to the surface of the cassava starch follows several mechanisms that can be combined. Capillary transport is a fundamental mechanism in case of porous products containing abundant amount of water. Based on the drying curve analysis, cassava starch drying was observed to occur during the falling rate period. During this period, the drying process is controlled by the diffusion of water, which can be characterized by effective

Figure 16. Cassava starch after drying.

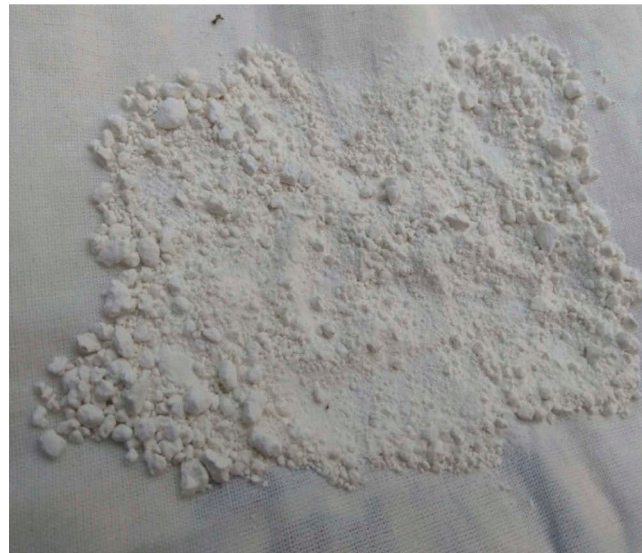


Table 4. Parameters used in the cassava starch drying thin-layer models

Model	T (°C)	k	N	a	b	R ²	RMSE
Newton	40	0.0035				0.9666	0.2051
	50	0.004				0.9662	0.1808
	60	0.0047				0.9668	0.1442
Page	40	0.0014	1.2012			0.9856	0.1319
	50	0.0013	1.2492			0.9893	0.1007
	60	0.0013	1.2791			0.9913	0.0702
Modified Page	40	0.0041	1.1911			0.9845	0.1379
	50	0.0044	1.1267			0.9813	0.1358
	60	0.0048	1.0542			0.9737	0.1288
Henderson and Pabis	40	0.0047		1.0901		0.9534	0.1562
	50	0.0047		1.0610		0.9596	0.1371
	60	0.0049		1.0198		0.9643	0.1308
Logarithmic	40	0.0043		1.0486	0.0070	0.9614	0.1556
	50	0.0048		1.0472	0.0070	0.9618	0.1363
	60	0.0054		1.0460	0.0068	0.9595	0.1226
Wang and Singh	40			0.0001	-2.23E-05	0.9604	0.2912
	50			0.0001	-2.47E-05	0.9652	0.2655
	60			0.0001	-2.80E-05	0.9490	0.2628
Midilli	40	0.0096	0.0063		-0.0028	0.9865	0.1373
	50	0.0096	0.0062		-0.0031	0.9890	0.1155
	60	0.0099	0.0062		-0.0034	0.9940	0.0712

*R² = determination coefficient; RMSE = Root Mean Square Error; k,n,a,b,c = model parameters.

diffusion (Koua et al., 2009). The effective diffusion (D_{eff}) was calculated by plotting the natural logarithm of the MR versus the drying time and then using Equation (11).

The modeled effective diffusivity increased with increasing temperature, as shown in Table 5. This is in accordance with the results obtained by Tzempelikos et al. (2015) and Jiang et al. (2017),

Figure 17. Experimental and predicted moisture ratio of cassava starch using the Page model at 60 °C.

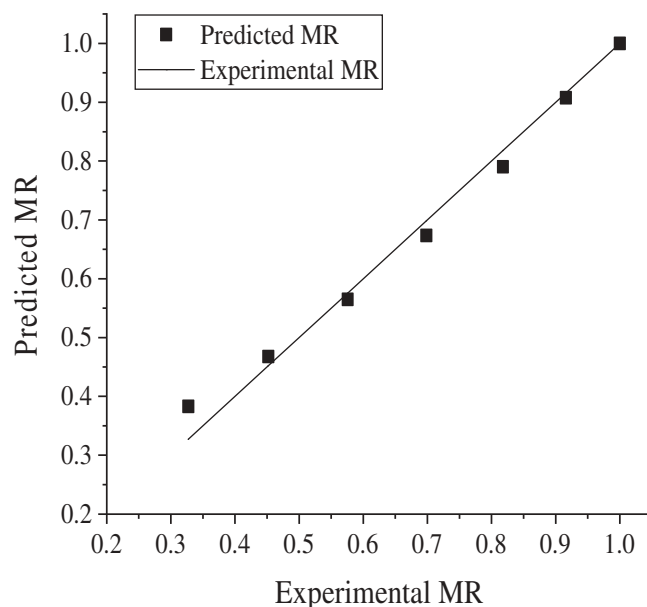


Table 5. Effective diffusivity at different drying temperatures

T (°C)	Effective diffusivity (m ² /s)
40	8.12×10^{-13}
50	1.04×10^{-12}
60	1.16×10^{-12}

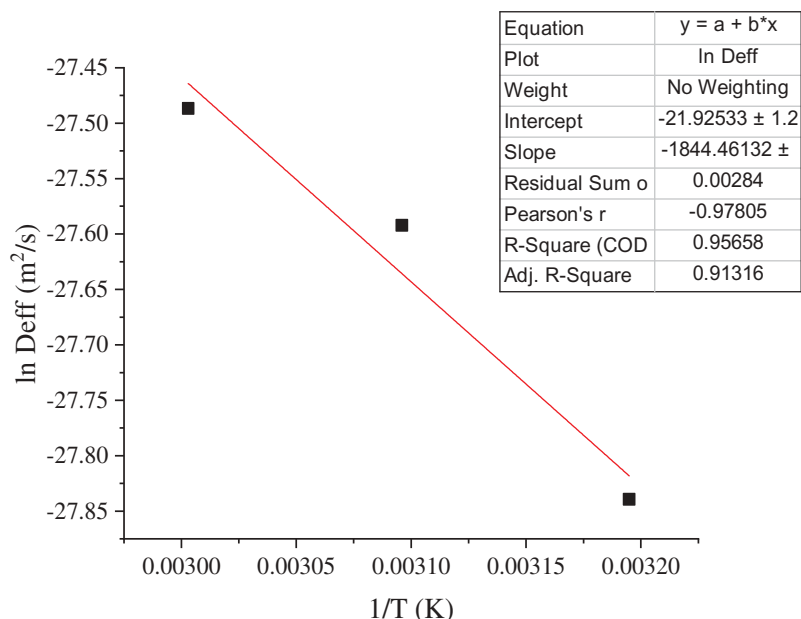
who observed that the effective diffusivity increased with increasing temperature. An increase in temperature reduces water viscosity and enhances the activity of water inside the starch, accelerating water diffusion toward the surface (Alara et al., 2019). According to Dairo et al. (2015), the generally accepted values with respect to the effective diffusivity of the agricultural and food products are 10^{-12} – 10^{-8} m²/s. Therefore, the effective diffusivity value obtained by drying at 40 °C did not satisfy the generally acceptable value.

The relation between effective diffusivity and drying temperature can be used to calculate the diffusivity coefficient at infinite drying temperatures (D_o , m²/s) and the activation energy (E_a) using Equation (13) and the effective diffusivity data at different temperatures. The natural logarithm of D_{eff} as a function of $1/T$ (where temperatures are in Kelvin) is shown in Figure 18. The resulting R^2 is 0.9566, indicating the good fitting of the prediction. The values of the intercept ($\ln(D_o)$) and slope (E_a/R) were -21.925 and -1844.46 , resulting in D_o and E_a being estimated as 3×10^{-10} m²/s and 15.3 kJ/mole, respectively. The activation energy was lower than that observed by other researchers, including Aviara and Igbeka (2016) in their work regarding cassava starch drying in a tray dryer (32.933 kJ/mole) and Shen et al. (2011) in their work regarding sorghum stalk drying using an oven dryer (21.4 kJ/mole).

4. Conclusions

In this study, a hybrid solar cassava starch dryer was proposed and experimentally analyzed with respect to their energetic and exergetic efficiencies at three different drying temperatures. The results indicated that 240 min, 210 min, and 180 min of hybrid solar drying were required at 40 °C, 50 °C, and 60 °C, respectively, to reduce the moisture content of the cassava starch to become less than 14% on a wet basis. The maximum overall energetic efficiency was 20.82%. The fluctuations

Figure 18. Plot of $\ln(D_{eff})$ vs $1/T$.



in exergetic flows were influenced by solar radiation during drying, and the overall exergetic efficiency ranged between 25.1% and 73.8%. The results indicated that the Page model is most suitable to describe the drying characteristics of cassava starch using the proposed hybrid solar dryer. The calculated effective diffusivity (D_{eff}) values during drying at 50 °C and 60 °C were in the range of the generally accepted effective diffusivity values with respect to agricultural products. Overall, the proposed hybrid solar dryer can be used to dry cassava starch even though further studies are needed to increase its energy and exergy efficiency and to improve its performance when used at temperatures of lower than 60 °C.

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