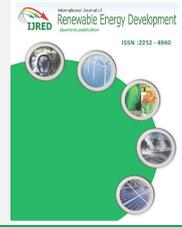




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Research Article

Energy Analysis of a Hybrid Solar Dryer for Drying Coffee Beans

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ABSTRACT. In this study, hybrid solar drying of coffee beans was performed, and energy analysis was carried out, to assess the system's performance, in terms of energy efficiency, compared to solar drying and the open sun drying method. The dryer has three compartments: solar collector for collecting solar radiation, drying chamber, and a Liquid Petroleum Gas burner, which acted as an auxiliary heater to assist the thermal energy. The drying chamber has four trays for placing the dried product. The initial moisture content of coffee beans was 54.23% w.b and was reduced to the final moisture content between 11-12% w.b. The coffee beans dried faster when subjected to the solar hybrid drying method, compared to other methods, with the dryer temperature of 40°C, 50°C, and 60°C. Results indicated that the coffee beans' drying times varied from 10 to 14 hours. However, at temperature 50°C and 60°C for the 1st tray, the water content was reduced more rapidly compared to the other tray. From the results of this study, we can see the different efficiency of solar collector that shows of 54.15% at variable temperature 60°C for drying time 12:00 to 14:00 p.m for hybrid solar drying and for the solar drying process is 50.07% at the range of drying time 12:00 to 14:00 p.m. Mathematical modelling shows that Page model is the most suitable for describing the coffee beans' drying behaviour using a hybrid solar dryer. The effective diffusivity values found in this experiment are all in the acceptable range for most agricultural products. ©2020. CBIORÉ-IJRED. All rights reserved

Keywords: Solar Drying, Hybrid Solar Dryer, Coffee Beans, Energy Analysis, Mathematical Modeling

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1. Introduction

According to the Coffee Market Report in December 2018, Indonesia was the fourth largest coffee-producing country, with a total production of 10.2 million tons in 2018 (International Coffee Organization, 2018). Over the last few years, market demands have increased, considering that daily coffee consumption has also increased. Studies had shown that coffee may have health benefits, including promoting calming effects and weight loss, and may prevent or delay diabetes by Greenberg et al. (2006). According to the Indonesia Standardization Body (2004), and Hanif *et al.* (2014), coffee with good quality has a moisture content of 11-12% w.b. The drying factor must be determined to achieve the desired water content. Both Aissa *et al.* (2014) and Dong *et al.* (2019) have the same understanding of drying; it is a complex process that involves the transfer of heat and mass between the product and the surrounding media.

The purpose of drying is to partially eliminate the moisture content from the products to reach the safe limit so it cannot become a medium for spreading

microorganisms, which may decrease the coffee bean quality (Suherman *et al.* 2018). Solar drying has been used for the preservation of food, agricultural, and marine products for a long time. This was particularly called natural convection drying under the direct sun. However, this natural convection drying is a relatively slow process in decreasing the water content in the product.

There are many obstacles in small industries during the drying process, such as contamination or insect infestation, depending on the availability of sunshine and inability to control the weather. This process causes the coffee bean's moisture content to be non-uniform. Therefore, the new technology for the drying process was developed to solve the problems mentioned above. This new technology is called a hybrid solar dryer, with sunlight as the main energy of the process supported by means of additional heating (Bennamoun *et al.* 2012; Kassem *et al.* 2011).

Several researchers have studied the application of the hybrid solar dryer for various products. A hybrid solar dryer system, which combines natural convection solar drying and a biomass burner, was studied experimentally

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by Prasad and Vijay (2005). The drying efficiency of solar-biomass hybrid dryer for ginger drying was calculated to be 15.59%. Al-Kayiem and Yassen (2016) have studied experimentally a hybrid solar thermal drying unit. The hybrid solar dryer system was constructed from a natural convection solar dryer, a natural convection thermal back-up unit, and a recovery dryer. The hybrid solar thermal drying efficiency for red chili drying was obtained as 9.9%.

Since measuring some variables during the drying process can be quite complicated, mathematical models can be used to simulate the distribution of temperature, moisture, and wind velocity during drying process. Mathematical models also allow for design and evaluation of dryer performance, control and optimization of the process, which is important in maintaining food safety and quality (Castro *et al.* 2018). Among many drying models, thin layer models can describe the drying phenomena in a united way, regardless of the controlling mechanism. They have been widely used to determine the drying kinetics of fruits and vegetables. For agricultural products, generally the moisture content of the material has been subjected to a constant relative humidity and temperature conditions is measured and correlated to the drying parameters. Thin layer modelling is simple to perform, and the model equations do not require evaluation of many model parameters, unlike more complex models (Kadam *et al.* 2011).

In this research, a newly-designed hybrid solar dryer (HSD) is applied to coffee beans. The dryer has three compartments: one for a solar collector for collecting solar radiation, a drying chamber, and a Liquid Petroleum Gas (LPG) burner to assist thermal energy. The drying chamber had four trays for spreading the product to be dried. This type of drying does not require large tracts of land and can be used in cloudy weather. External intervention can also be minimized. This technology is renewable, environmentally friendly, and economically sustainable for most developing countries. Therefore, the aims of the research are to study the HSD's performance for drying coffee beans and solar drying without a LPG burner. The drying curve and drying rate of coffee beans, the drying temperature profile, energy analysis, and mathematical modelling of HSDs were also investigated.

2. Materials and Methods

2.1 Materials

The raw material used in this study is robusta coffee beans. They were taken from UKM (Small and Medium Enterprises) in Mungseng District, Temanggung Regency, Central Java because they are the most widely consumed.

2.2 Experimental procedure

This research was conducted from 08:00 a.m to 04:00 p.m. During the experiment, coffee beans were spread on the tray in the drying chamber. In the hybrid solar dryer, hot air flowed from the bottom of the aluminum rack, which comes from the LPG burner, to speed up drying.

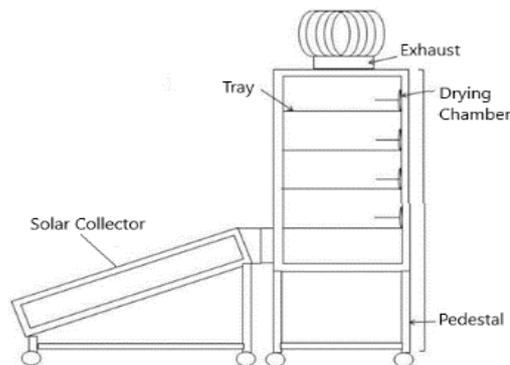


Fig 1. Schematic diagram of solar dryer



Fig 2. Complete view of hybrid solar dryer

During the process, temperature, relative humidity, solar intensity, the velocity of air, and the mass of coffee beans was measured once every 60-minutes. The air temperature is measured by a relative humidity meter with an accuracy of $\pm 0.5^{\circ}\text{C}$.

Fig. 1 shows the schematic diagram of the solar dryer, while Fig. 2 shows the complete view of the HSD. The solar dryer's components were made from aluminum, which has good heat conductivity, is relatively light, durable, and easy to find. The transparent cover of the dryer and solar collector is made from glass due to its good absorbability to solar radiation, light-weight, and easy to get (Beristain *et al.* 1994). Table 1 summarizes the HSD specifications used in this experiment.

2.3 Drying Process

The experiments were performed in the Laboratory of Chemical Engineering Department, Diponegoro University, Semarang, Indonesia. The coffee beans used in this process had initial moisture content 54.23% w.b. Its determination based on the AOAC method by Fudholli, et al (2016). There were three drying in this experiment: hybrid solar drying, solar drying, and natural convection drying.

For open sun drying (OSD), 300 grams of coffee beans were spread above the aluminum tray and dried under the sky until the moisture was under 12% w. b. The weight of the sample was measured once every 60 minutes. This data is required to analyze the effectivity factor of a HSD. The equipment needed are digital scales, a Relative Humidity meter with a temperature unit (@Krisbow S000052505), a solar intensity meter, and an anemometer.

Table 1
Specifications of hybrid solar dryer

Components	Specifications
Solar Collector	
Type	Flat
Area	1 m ²
Glass thickness	2 mm
Black body	PVC, 1 mm
Degree of inclination	40 °
Drying Chamber	
Tray size	1 x 0.6 x 0.94 m
Tray area	0.56 x 0.45 m
Exhaust	Diameter: 0.36 m Height: 0.4 m
Pedestal	1.01 x 0.61 x 0.52 m
Blower	
Capacity	0.38 KW
Velocity	0-3800 rpm
Voltage	110 V

As for the HSD, the independent variable is the drying temperatures, i.e., the LPG burner temperature setting at 40, 50, and 60 °C, respectively. To begin the experiment, 4 samples @300 grams of coffee beans were prepared for each tray. The dryer is prepared by connecting the drying chamber, solar collector, and LPG burner. Then the blower in LPG burner is turned on to blow hot air to the bottom part of the drying chamber. The drying process was performed from 08.00 a.m to 04.00 p.m. until the moisture content under 12% w.b. Using its respective measurement equipment, the temperature, RH, solar intensity, and mass of coffee beans was measured once every 60 minutes. Air temperatures of the inlet dryer (solar collector inlet), dryer chamber, and outlet dryer were measured.

The last drying mode is solar drying (SD) without the LPG burner. The data was measured using the same mode as before.

3. Analysis

The coffee beans' initial moisture content can be evaluated on a wet and dry basis which is stated in percent for every 60 minutes according to the following equations by Aissa, *et al* (2014) and Yassen *et al* (2016):

$$Mc (wet base) = \frac{M_i - M_d}{M_i} \times 100 \tag{1}$$

$$Mc (dry base) = \frac{M_i - M_d}{M_i} \times 100 \tag{2}$$

Aside from being used to determine the moisture content of coffee beans, the coffee beans's weight can also be used to determine the drying rate (R_d, in g/ hour) at any given time (t, hour), using Equation 3 by Deeto *et al* (2018):

$$R_d = \frac{M_i - M_d}{t} \tag{3}$$

Where M_i is initial mass (g); M_d is mass after drying (g); R_d is drying speed; t is drying time (hour). Dong *et al.* (2017) calculated the specific energy consumption (SEC) of the hybrid solar drying system as:

$$SEC = \frac{w}{q} \tag{4}$$

Where Q is the total energy input to dryer (kWh/g); SEC is specific energy consumption (kWh). The efficiency of the solar collector was estimated according to the following equation by Bennamoun (2012) and Dong *et al* (2017):

$$\eta_c = \frac{W \times L}{I \times A} \tag{5}$$

Where η_c is collector efficiency; W is mass water removed from the wet product (kg); L is heat of water vaporization at the exit air temperature (J/kg); I is Intentional sunlight (W / m²); A is Collector area (m²). Fudholli *et al* (2016) and Ayensu *et al* (1997) calculated the efficiency of the hybrid solar drying system, which was estimated according to the following equation:

$$\eta_d = \frac{W \times L}{(I \times A) + (Pf) + (MB \times LCV)} \tag{6}$$

Where η_d is hybrid solar drying efficiency; Pf is fan power (watt); MB is mass of fuel consumed (kg); LCV is Lower Calorific value of fuel (J/Kg).

In this experiment, seven thin-layer drying models were used to determine the most suitable model that can describe the coffee beans' drying behavior using a HSD. Mathematical modeling was performed using MATLAB software. Table 2 shows the drying models used. These thin layer drying models are often used on fruits and vegetables (Onwude *et al.* 2016). A new parameter, namely Moisture Ratio (MR) is defined using Equation 7 (Dairo *et al.* 2015).

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{7}$$

M is the moisture content at any given time, while M₀ is the initial moisture content, and M_e is the equilibrium moisture content. However, in this experiment, the relative humidity values varied continuously during drying and the values of M_e are relatively small compared to M or M₀ (Dairo *et al.* 2015; Sanni and Odukogbe 2015). Therefore, Equation 7 can be simplified into Equation 8.

$$MR = \frac{M}{M_0} \tag{8}$$

Table 2
Thin-layer drying models

Model	Formula	References
Newton	MR = exp(-kt)	El-Beltagy <i>et al.</i> 2007
Page	MR = exp(-kt ⁿ)	Tzempelikos <i>et al.</i> 2014
Modified Page	MR = exp[-(kt) ⁿ]	Vega <i>et al.</i> 2007
Henderson and Pabis	MR = a exp(-kt ⁿ)	Hashim <i>et al.</i> 2014
Logarithmic	MR = a exp(-kt) + c	Kaur and Singh 2014
Midilli <i>et al.</i>	MR = a exp(-kt) + bt	Ayadi <i>et al.</i> 2014
Modified Midilli <i>et al.</i>	MR = a exp(-kt) + b	Gan and Poh 2014

Two parameters were used to evaluate the drying models' accuracy, namely the correlation coefficient (R^2) and Root Mean Square Error (RMSE). The model with the highest value of R^2 and lowest value of RMSE will be chosen as the most suitable model (Charmongkolpradit and Luampon 2017). The value of R^2 and RMSE can be determined using Equation 9 and 10 (Dhanushkodi *et al.* 2017).

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2} \quad (9)$$

$$R^2 = \frac{[\sum_{i=1}^N (MR_{exp,i} - MR_{exp}) (MR_{pre,i} - MR_{pre})]^2}{\sum_{i=1}^N (MR_{exp,i} - MR_{exp})^2 \sum_{i=1}^N (MR_{pre,i} - MR_{pre})^2} \quad (10)$$

According to Ertekin and Firat (2015), drying characteristics in the falling rate period can be described using Fick's diffusion equation. Assuming long drying time, uniform moisture distributions, and slab geometry for coffee beans, Equation 11 can be used (Tzempelikos *et al.* 2015).

$$MR = \frac{8}{\pi^2} \exp\left[-\frac{D_{eff} \pi^2}{4L^2} t\right] \quad (11)$$

Where D_{eff} is effective diffusivity (m^2/s), L is the half-thickness of coffee beans (m), t is drying time (s), and π is a constant. By changing Equation 11 into logarithmic form, a new linear equation is obtained, as shown in Equation 12. The value of D_{eff} can be obtained by plotting MR and t in a linear graph. All calculations of D_{eff} are performed using Microsoft Excel.

$$\ln MR = \ln \frac{8}{\pi^2} - \left[\frac{D_{eff} \pi^2}{4L^2} t\right] \quad (11)$$

4. Results and Discussion

4.1 Profile of temperature, relative humidity and solar intensity during coffee beans drying

A Hybrid SD System for drying coffee beans has experimented. The coffee beans were dried to 11%–12% w.b from 54.23% w.b. of the moisture content. The variations of solar intensity, ambient temperature, ambient relative humidity is shown in Fig.3a-b, during the drying of coffee beans using a HSD at 60 °C and 50 °C.

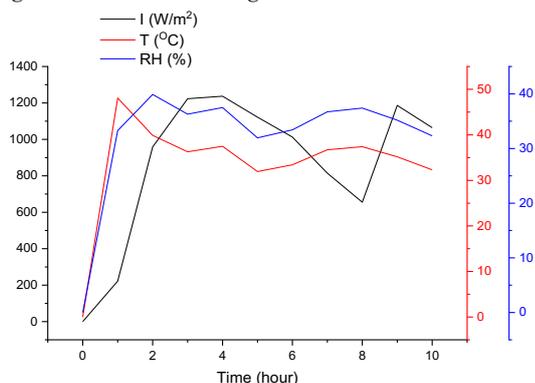


Fig 3a. The profiles of temperature, relative humidity, and solar intensity of ambient at HSD 60°C

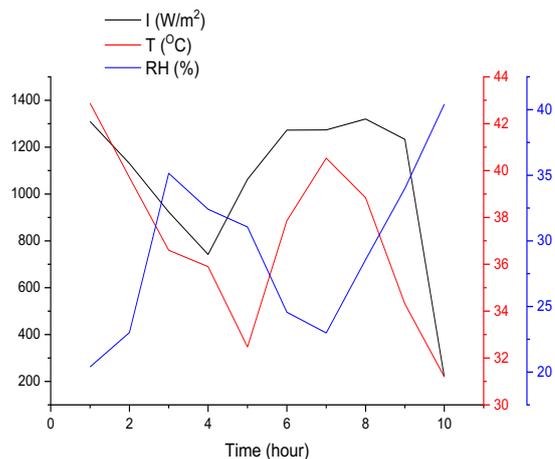


Fig 3b. The profiles of temperature, relative humidity, and solar intensity of ambient at HSD 50°C

For Fig.3a, it is shown that the ambient relative humidity ranged from 31 to 38%, the highest solar intensity is 1186 W/m^2 at 9th hours of the drying time. Meanwhile, for Fig.3b, it is shown that the highest of solar intensity is 1320 W/m^2 at 8th hours of the drying time with the relative humidity of ambient ranged from 20 to 40%, which is fluctuating up and down this is same as previous investigation by Kumar *et al.* (2016).

4.2 Analysis of moisture content curve

The amount of final moisture content ranges from 11 to 12 per cent w.b, which is equivalent to 150 - 152 kg. According to Figure 4a-d, the moisture content of the product decreased rapidly when the temperature of the hybrid solar dryer at 60 °C with low relative humidity.

However, there are no significant differences between the temperatures of 60 °C and 50 °C this may cause the heat of solar that has been collected for experiment at 50 °C due to good solar intensity radiation in that time, with an average value of 1059.49 W/m^2 . The higher of solar radiation, the higher the air temperature will be. High-temperature air picks up air more quickly from food ingredients so the drying process becomes faster. It is the same as what has been studied by Agustina *et al.* (2016).

The OSD operating mode only has one data as a comparison base. Fig.4a-d shows the variations of moisture content vs drying time. It is seen that the moisture content at the first tray is lower than the other tray. That is because the heat which is received by first tray is highest than the above tray. The heat will decrease after passing the first tray that is because the distance of the heat source (LPG burner outlet and solar collector outlet) is getting farther, this result is similar that during the combustion process of gas with high temperature, samples in the bottom tray dried faster (Yassen, *et al.*, 2016).

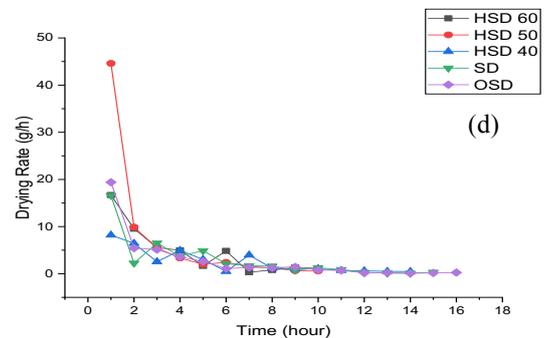
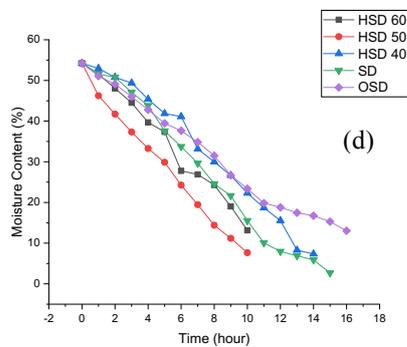
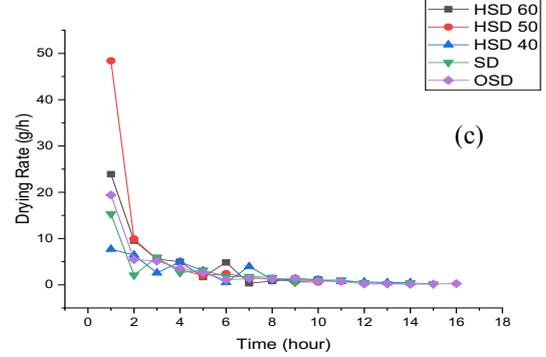
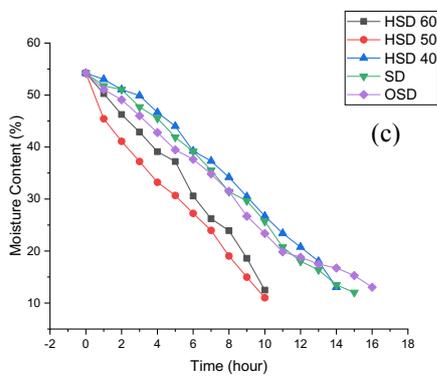
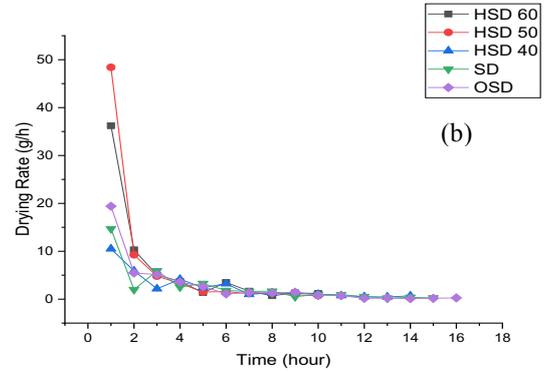
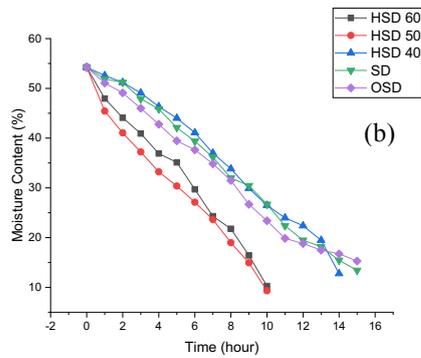
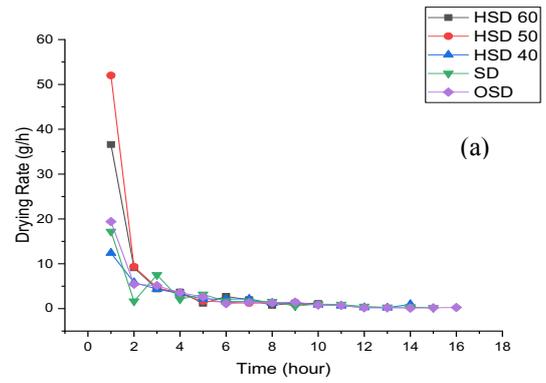
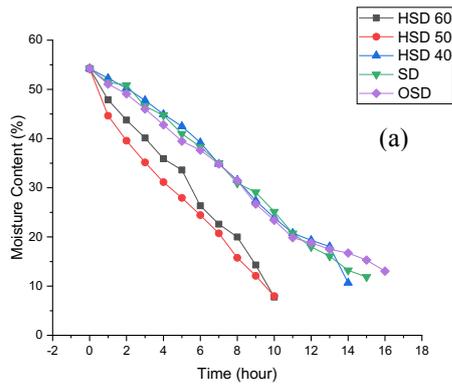


Fig. 4. Moisture content versus drying time at (a) first tray, (b) second tray, (c) third tray and (d) fourth tray

Fig. 5 Drying rate versus time curve at (a) first tray, (b) second tray, (c) third tray and (d) fourth tray

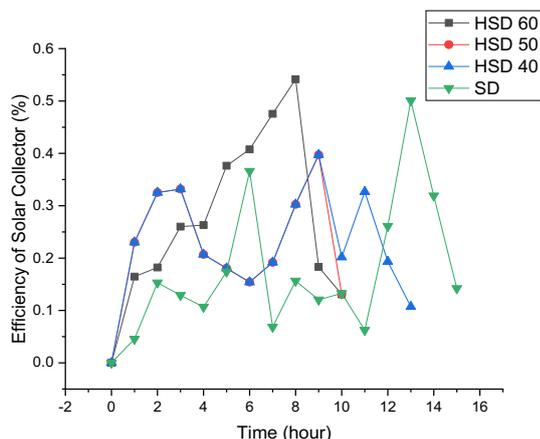


Fig. 6. Efficiency of solar collector

The fourth tray shows something different. The fourth tray is right under the sky and the glass will absorb heat from the sun directly, so that tray fourth has a higher temperature than the temperature of the tray below. In addition, it should be seen that the longer the drying time, the more the water content decreases until it becomes constant. Based on Tashtosh *et al* (2014) the drying rate decreases over time due to the moisture content inside the coffee beans, which also decreases over time.

4.3 Analysis of drying rate

The coffee beans drying rates under different temperatures and methods is shown in Fig. 5a-d. The result shows that coffee beans dried by HSD faster at temperature 50°C (average drying rate on the first until the fourth tray are 6.99 g/h, 6.63 g/h, 6.87 g/h and 6.53 g/h) and at temperature 60°C (average drying rate on the first until the fourth tray are 5.71 g/h, 5.91 g/h, 4.92 g/h) and 4.26 g/h than other temperature and methods. It took 10 hours to dry 300 g of coffee beans. In this case, drying is influenced by the burner gas temperature and the sunlight intensity (Harun *et al*, 2016).

Coffee bean drying at temperature 40°C by HSD has taken 14 hours of the drying process (average drying rate for each tray are 2.72 g/h, 2.52 g/h, 2.48 g/h and 2.51 g/h). The average drying rate for each tray is 2.69 g/h, 2.49 g/h, 2.55 g/h and 2.88 g/h. The drying process for mode SD took 15 hours. Mode OSD took 16 hours, and the average drying rate is 2.48 g/h. A study by Siddique and Wright (2003) concluded that the higher the temperature, the faster the drying time.

4.4 Analysis of energy efficiency

The Solar Collector efficiency depends on various parameters, such as the solar intensity, the ambient air velocity, ambient temperature, and internal parameters such as the surface area of the black body, type of glass material, and the glass thickness. It is seen from Fig. 6 that the highest solar collector efficiency shows about 54.15% at temperature 60°C at 12:00 a.m to 14:00 p.m drying time and during the SD operation the efficiency is about 50.07% at 12:00 a.m to 14:00 p.m drying time.

Meanwhile, Fig. 7 shows that the efficiency for HSD operation mode is greater than SD operation mode, it is about 79.78 per cent for temperature 40°C. The fluctuation on the graphic is because of the difference in solar intensity for day to day and that is same as what has been studied by Sengar *et al*. (2009). The total energy required for temperatures of 60 °C, 50 °C, and 40 °C there is 99.21 kWh, 116.29 kWh and 277.57 kWh with consideration of the longer time for drying than other temperature variables.

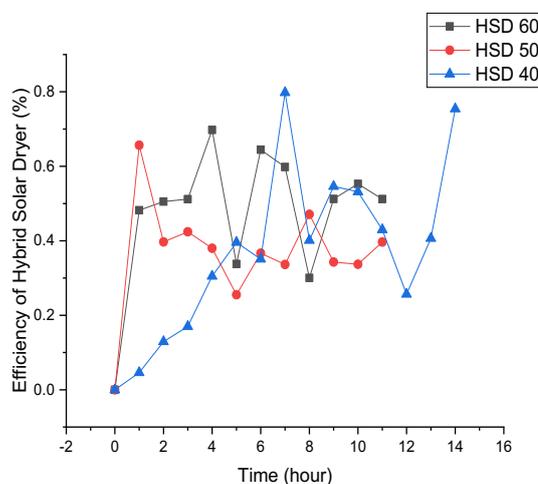


Fig. 7. Efficiency of hybrid solar drying

4.5 Mathematical modeling

The MR data obtained from the experiment are plotted into seven thin-layer drying models to determine the best model to describe the coffee beans' drying behavior using a HSD. In this model, only tray 1 is modeled since it gives the fastest moisture reduction compared to the other trays. Table 3 shows the modeling results, including all of the models' parameters, as well as the values of R² and RMSE.

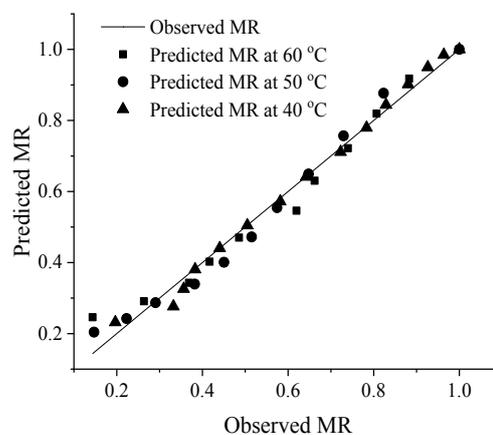


Fig. 8. Plot of observed MR and predicted MR using page model at 40, 50, and 60 °C

Table 3

Parameter values from thin layer modeling of coffee beans drying

Models	T (°C)	k	n	A	b	c	R ²	RMSE
Newton	40	0.0713					0.9600	0.0711
	45	0.1325					0.9668	0.0426
	50	0.1508					0.9792	0.0362
	55	0.1210					0.9723	0.0430
	60	0.1238					0.9586	0.0590
Page	40	0.0157	1.7183				0.9939	0.0220
	45	0.1082	1.1194				0.9645	0.0497
	50	0.1317	1.0816				0.9807	0.0354
	55	0.0831	1.2181				0.9795	0.0349
	60	0.0859	1.2127				0.9725	0.0431
Modified Page	40	0.0784	1.1985				0.9788	0.0490
	45	0.1381	1.1480				0.9636	0.0519
	50	0.1543	1.1142				0.9808	0.0361
	55	0.1345	1.3881				0.9793	0.0413
	60	0.1390	1.4842				0.9782	0.0420
Henderson and Pabis	40	0.0157	1.7238	1.0051			0.9938	0.0238
	45	0.0597	1.4768	1.0095			0.9491	0.0852
	50	0.0721	1.4323	0.9952			0.9749	0.0571
	55	0.0691	1.3249	1.0007			0.9797	0.0381
	60	0.0764	1.3075	1.0214			0.9735	0.0438
Logarithmic	40	0.0939		0.9459		0.1046	0.9433	0.0668
	45	0.1696		0.9273		0.1052	0.9581	0.0501
	50	0.1764		0.8683		0.1077	0.9716	0.0470
	55	0.1378		0.8561		0.1152	0.9660	0.0562
	60	0.1593		0.8341		0.1551	0.9402	0.0743
Midilli et al.	40	0.0716		1.0006	0.000108		0.9597	0.0711
	45	0.1378		1.0187	0.000102		0.9657	0.0466
	50	0.1535		1.0086	0.000105		0.9784	0.0368
	55	0.1253		1.0158	0.000099		0.9707	0.0420
	60	0.1256		1.0063	0.000101		0.9576	0.0582
Modified Midilli et al.	40	0.0829		1.0230	0.0262		0.9518	0.0616
	45	0.1438		0.9953	0.0253		0.9645	0.0470
	50	0.1575		0.9757	0.0248		0.9774	0.0379
	55	0.1296		0.9893	0.0250		0.9691	0.0434
	60	0.1299		0.9795	0.0250		0.9557	0.0601

Mathematical modeling results show that the values of R² and RMSE differ randomly and do not follow a specific pattern. It can be seen from the table that the Page model has the highest average value of R² and lowest average value of RMSE. Therefore, Page model is the most suitable model for describing the drying behavior of coffee beans, followed by the Modified Page model and the Henderson and Pabis model. However, other research about thin-layer drying of coffee report that Midilli *et al.* model is the best model (Siqueira *et al.* 2016; Deeto *et al.* 2018), while Phitakwinai *et al.* (2019) found that Modified Midilli *et al.* model is the best model, although the Page model also described the coffee beans' drying behavior. These differences in best model selection may be caused by different drying methods and conditions (Onwude *et al.* 2016). Fig. 8 shows the plot of observed MR and predicted MR using the Page model at 40°C, 50°C, and 60°C.

Drying the biological products during the falling rate period is controlled by the mechanism of liquid and/or vapor diffusion, assuming that the resistance to moisture flows is distributed uniformly through the interior of the material. The rate of moisture movement is described by an effective diffusivity value (D_{eff}), no matter which mechanism of diffusion is involved (Ertekin and Firat, 2015). Table 4 shows the value of effective diffusivity at different drying temperatures. The effective diffusivity values in this experiment are found to be within a range of 10^{-11} to 10^{-9} m²/s, which is generally considered the

acceptable range for most agricultural and food products (Aviara *et al.* 2016). Another study, performed by Phitakwinai *et al.* (2019), reports that the effective diffusivity values of coffee beans dried at 50°C–70°C ranged from $7.7544 \cdot 10^{-10}$ to $1.4525 \cdot 10^{-9}$. It can be seen that higher temperature will increase the effective diffusivity value (Alara *et al.* 2017). Drying at high temperature will increase the product's temperature, which promotes water movement inside the product through diffusion and then evaporates into the air (Phitakwinai *et al.* 2019; Alara *et al.* 2017).

Table 4

Values of effective diffusivity of coffee beans at different drying temperatures

Temperature (°C)	Effective Diffusivity (m ² /s)
40	1.80×10^{-10}
45	1.96×10^{-10}
50	2.40×10^{-10}
55	2.72×10^{-10}
60	2.87×10^{-10}

5. Conclusion

In this research, the drying experiment of coffee beans using a HSD was performed. All coffee beans were dried to the final moisture content of < 12% w.b from 54.23% w.b with different lengths of time. Drying at 60°C and at the

first tray gives the best result. Higher drying temperature will lead to faster moisture reduction, and the moisture reduction is at its fastest during the initial drying phase. The SEC was 99.21 kWh, 116.29 kWh and 277.57 kWh for temperatures of 60°C, 50°C, and 40°C. The geographic condition, location factor, and time of measurement are very influential in the drying process. Besides that, try to apply the other material for the solar collector, such as the quartz glass that may increase solar heat adsorption. Mathematical modeling shows that the Page model is the most suitable for describing the coffee beans' drying behavior using a HSD. The effective diffusivity values in this experiment are all in the acceptable range for most agricultural products.

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