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Hybrid solar dryer for sugar-palm vermicelli drying

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Abstract

Sugar palm is an abundant palm in Indonesia and widely used for various foods, one of which is vermicelli. During vermicelli production, local farmers still implement open-sun drying, which reduces the quality of vermicelli, requires long periods of time, and cannot be performed during poor weather. Therefore, in this study, a new method of vermicelli drying is introduced using a hybrid solar dryer, which consists of a solar dryer and an additional heater powered by liquefied natural gas. Hybrid solar drying is conducted at 40, 60, 80, and 100°C. With 2 hr of drying time, the final moisture contents of vermicelli dried using hybrid solar dryer have satisfy the standard limit, while the open-sun drying and natural solar drying do not, indicating that hybrid solar drying is faster and more effective. Vermicelli drying occurs at the falling-rate period and increasing drying temperature from 40 to 100°C increases dryer efficiency, energy utilization ratio, and exergy efficiency, from 13.02 to 17.02%, from 0.18 to 0.32, and from 67.4 to 83.6%, respectively. Although the overall quality of dried vermicelli is acceptable, increasing drying temperature from 40 to 100°C result in the damaged vermicelli surface as evident from *SEM* analysis and degradation of vermicelli whiteness value from 87.2 to 82.5.

Practical applications: The drying process is playing an important role in heat sensitive products dehydration. The present study provides an investigation of potential use of solar energy for drying of vermicelli which combine with the natural gas heating process. The results show that hybrid drying system could enhance the product quality of vermicelli and also reduce the drying process. During drying, proximate components of vermicelli essentially do not change but it alters the color of product.

1 | INTRODUCTION

Sugar palm (*Arenga pinnata*), usually called aren in Indonesia, is mostly found in Southeast Asia, particularly in Indonesia and Malaysia. In Indonesia, sugar-palm production area reached around 70,000 ha in 2014 and can be found in almost every provinces in Indonesia, from Papua to Sumatera (Indonesian Ministry of Agriculture, 2014). Sugar-palm starch, which is located at the trunk of the tree, is usually converted into sugar during flowering. When the sugar palm is not productive, the starch from the trunk can be extracted and utilized for other purposes (Sanyang, Sapuan, Jawaid, Ishak, & Sahari, 2016). Sugar palm is an important source of starch, especially in Indonesia, since the trees contain 10.5 to 36.7% starch content (Adawiyah, Sasaki, & Kohyama, 2013). On average, each sugar-palm trunk produces ~60–70 kg of starch. In Indonesia, it is widely used as a material for a variety of food, including cakes, meatballs, noodles, and vermicelli (Suherman & Hidayati, 2018).

During vermicelli production, after the sugar-palm starch is cooked and pressed, it is dried under the sun for ~4 hr. Drying holds an important role in vermicelli production since it can preserve quality while reducing weight and volume (Berk, 2018). Since the majority of vermicelli producers in Indonesia are located in rural areas, they rely on a traditional drying method using the sun. Although the said method is cheap and easy to perform, the drying process cannot be controlled and the dried vermicelli is prone to degradation due to environmental exposure. Moreover, during the wet season, drying is not possible, which drastically reduces vermicelli production (Pranoto, 2015). Therefore, a new drying method is required to solve this problem.

Unfortunately, relatively few studies have discussed new technology for vermicelli drying. Yosua and Rahayu (2014) studied the vermicelli drying process with an oven using gradual heating, finding that increasing the temperature from 80 to 130°C for a total time of 25 min sufficiently dried the vermicelli to a 13.09% wet basis, with an estimated 33% of drying costs saved for 80 tons of vermicelli produced every month. Chan and Darius (2018) analyzed vermicelli drying using an automatic conveyor hybrid dryer, finding that the dryer was able to reduce vermicelli weight from 2 to 1 kg in 50 min using solar radiation and, when using gas as a fuel, the same reduction was obtained in 28.39 min. Although both studies provide new insights concerning improvements in vermicelli drying, they made use of mechanical energy-driven dryers, which are not economical due to high-energy costs (Deshmukh, Varma, Yoo, & Wasewar, 2014).

Solar drying is a potential vermicelli drying method for several reasons. Firstly, it provides protection to the dried material while being economical and favorable for local vermicelli farmers due to the unlimited heat source. Secondly, it's a green process, due to solar energy being a nonpolluting energy source, which makes it one of the most promising alternative energy source (Deshmukh et al., 2014; Mennouche, Boubekri, Chouicha, Bouchekima, & Bouguettaia, 2017). However, similar to open-sun drying, solar drying cannot be performed during the wet season (Imre, 2014). To solve this problem, an additional heat source is equipped to the solar dryer, thereby enabling operation regardless of the weather conditions. These dryers are called hybrid solar dryers due to the implementation of solar energy and conventional energy sources (Gudiño-Ayala & Calderón-Topete, 2014). Various types of hybrid solar dryers have been developed for many agricultural products, such as solar biomass hybrid dryer for maize (Bosomtwe et al., 2019) and gas-fired hybrid solar dryer for onion and ginger (Anum, Ghafoor, & Munir, 2017). However, to the best of the authors' knowledge, the application of hybrid solar drying for vermicelli is yet to be examined. Therefore, this study aims to investigate the performance of a hybrid solar-dryer (HSD) prototype for sugar-palm vermicelli drying, wherein an indirect and forced convection solar dryer is combined with liquefied petroleum gas (LPG) as an additional heat source. To assess the performance of the hybrid solar dryer, the drying curve, dryer efficiency, exergy usage, improvement potential, and vermicelli quality are analyzed.

2 | MATERIALS AND METHODS

2.1 | Experimental setup

This research was conducted over the course of 3 months; it was carried out at the Chemical Engineering Waste Treatment Laboratory, Diponegoro University. Figure 1 shows the schematic of the hybrid solar dryer, and Figure 2 shows a photograph of the dryer along with

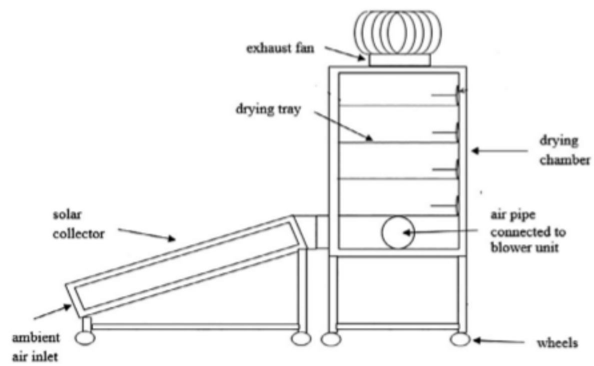

FIGURE 1 Schematic of hybrid solar dryer

FIGURE 2 Hybrid solar dryer with blower and burner unit

the blower and burner unit. The drying-chamber wall is made from glass and has four levels, each with two trays placed side by side. Each tray is covered with aluminum coverings at the side edge. The solar collector is made from glass with a black absorber inside to enhance the absorption of solar radiation. Nine air holes can be found at the bottom of the solar collector, which allow ambient air to flow inside by convection. In particular, the blower sucks ambient air, passing it through the burner unit to be heated by LPG indirectly, after which point it flows into the drying chamber through the air pipes connecting the burner unit and drying chamber. The convective drying air from the solar collector and the drying air from the burner unit collect at the bottom of the first tray, after which point the drying air flows upward through the trays and exits through a chimney installed at the top of the drying chamber. The specifications of the hybrid solar dryer are shown in Table 1, while technical details of the solar collector are shown in Table 2.

The measurement devices needed in this experiment are Krisbow Electronic Kitchen Scale 5 kg Slim Plate digital weigher (accuracy ±0.1 g), Bonad SM206 Solar Power Meter to measure the solar intensity (accuracy ±0.1 W/m^2), Krisbow KW0600561 Digital Temperature and

TABLE 1 Specification of hybrid solar dryer

No.	Parts	Material	Specification/information
1.	Drying chamber	Glass and aluminum	100 × 60 × 94 cm (length × width x 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 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 has a 6 cm diameter

Relative Humidity meter (accuracy ±0.1°C and ± 0.01%, respectively), Krisbow KW0600562 Flexible Thermo Anemometer Unit (accuracy ±0.01 m/s), and Digital Multimeter Fluke 117 True RMS Original (accuracy ±0.1 A and ± 0.1 V). The temperature of the air was monitored at primary solar collector, drying chamber, and at the exit of drying chamber by PT-100 sensor thermocouples with accuracy of ±0.5°C.

2.2 | Experimental procedures

2.2.1 | Vermicelli pretreatment

Wet vermicelli (6.2 kg) was purchased from Sriti Bird *SME* in the Klaten Regency, Central Java, Indonesia. Each drying tray contained 50 g of wet vermicelli. A total of 1.6 kg of wet vermicelli was used and divided into eight trays for each temperature variable, that is, 40, 60, 80, and 100°C. We selected drying temperature of 40, 60, 80, and 100°C to better understand the effect of temperature to the quality of dried vermicelli and the moisture reduction. We took 40°C as a starting temperature because it is generally the highest possible temperature achieved by traditional drying in our region. For solar drying without additional energy from LPG gas, 400 g of wet vermicelli was used. The open-sun drying method was also performed, using 50 g of wet vermicelli placed on a small tray and left open under the sun. Using the oven-drying method (Nielsen, 2010), the initial moisture content of vermicelli was determined, which was 38.2 ± 0.37% wet basis.

2.2.2 | Drying process

All the drying process were performed on March 11 to 28, 2019. Three drying methods were carried out with a drying time of 2 hr for each, running from 10:00 a.m. to 12:00 p.m. The first method consisted of drying wet vermicelli under the sun. The second method consisted of natural drying using a solar dryer without additional energy from LPG. The third method consisted of the hybrid solar dryer and additional LPG energy, with temperature variations of 40, 60, 80, and 100°C. The gas regulator on the LPG was constantly regulated and kept in check to ensure that the temperature inside the drying cabinet matched the desired temperature variable. During the experiment, the weather was sunny with only few clouds. The experiment was initiated by weighing the vermicelli into 50 g for each tray. Experimental data were recorded every 10 min. Vermicelli-mass data was obtained using digital scales. Relative humidity, temperature, and solar-radiation intensity (in the ambient air, collector, and drying chamber) were measured using a temperature-relative humidity meter and a solar-power meter. The drying-chamber air-flow and blower electrical current were obtained using an anemometer and multimeter, respectively. The LPG was also weighed every 10 min.

2.2.3 | Statistical analysis

All drying experiments were performed in triplicate. The average data was taken for graphical analysis, along with the *SD* of each data, which represents the deviation/error that may occur during data measurement. The *SD* from triplicate measurements were expressed in vertical bars on each data point on the graphs. The air temperature and relative humidity of ambient air were measured every 10 s for 60 s total to check the measurement accuracy of the temperature and relative humidity meter. Solar intensity was also measured within the same time period to check the accuracy of Solar Power Meter. Airflow inside hybrid solar dryer, blower voltage and blower current were measured every 10 s for 60 s using the respective measurement tools by operating the drying without load. The accuracy of digital weigher was determined by weighing the intial weight of vermicelli (which is 50 g) for the same time period as previously mentioned. The uncertainty can be expressed using Equation (1) (Sarker, Ibrahim, Abdul Aziz, & Punan, 2015):

$$x_i = x_{mean} \pm \delta x_i \tag{1}$$

Where x_i is the actual value of measured data, x_{mean} is the mean value of the measurements, and δx_i is the uncertainty. From this calculation, the value of fractional uncertainty can be determined by dividing δx_i with x_{mean}. Since the value of fractional uncertainty is small, it would be more convenient to multiply the value with 100 and report it as percent uncertainty. As shown in Equation (2) (Sarker et al., 2015). The values of percent uncertainty from all measurement devices are shown in Table 3. Using the same formula, maximum percent uncertainties during the calculations of collector efficiency, dryer efficiency, exergy efficiency, and improvement potential (IP) were also determined (Lakshmi, Muthukumar, Ekka, Nayak, & Layek, 2019), with the value of ±3, ±2.31, ±1.64, and ± 3.41%, respectively.

$$\text{Percent uncertainty} = \text{Fractional uncertainty} \times 100 \tag{2}$$

2.3 | Data analysis

2.3.1 | Moisture-Content analysis

To calculate moisture content, the weight of both dry and wet vermicelli must be obtained. Thereafter, Equation (3) can be used to calculate the moisture content of vermicelli in % wet basis (X_w) (Visavale, 2012):

$$X_w = \frac{M_w}{M_w + M_d} \times 100 \tag{3}$$

where M_w denotes the mass of water (g) and M_d denotes the mass of dry vermicelli (g).

2.3.2 | Drying-Rate analysis

Drying rate (R_d, g/min) can be calculated by dividing the vermicelli weight reduction at two subsequent measurements ($m_{t+\Delta t}$-m_t, g) with intervals of drying time (t, min), as shown in Equation (4) (Dhanushkodi, Wilson, & Sudhakar, 2014):

$$R_d = \frac{M_{t+\Delta t} - M_t}{t} \times 100 \tag{4}$$

2.3.3 | Collector efficiency

To obtain the collector efficiency, Equation (5) can be used (Dhanushkodi et al., 2014):

$$\eta_c = \frac{m.C_{pda}.(T_o - T_i)}{I.A} \tag{5}$$

where η_c denotes the collector efficiency, I the intensity of solar radiation (kW/m^2), A the surface area of the collector (m^2), m the flow rate of drying air (kg/s), C_{pda} the specific heat of drying air (kJ/kg °C), T_o the collector exit temperature (°C), and T_i the collector entry temperature (°C).

2.3.4 | Dryer efficiency

Dryer efficiency is the ratio of energy used to evaporate water to the total energy supplied by the dryer. Equation (6) shows the calculations based on this definition (Dhanushkodi et al., 2014):

$$\eta_d = \frac{m_w.h_{fg}}{I.A.t + E + m_{fuel}.C_v} \times 100 \tag{6}$$

where η_d denotes the efficiency of the drying chamber (%), m_w the mass of evaporated water at any time during drying (g), h_{fg} the latent heat of water vapor (kJ/kg), E the blower energy (kWh), m_{fuel} the mass of LPG (kg), and C_v the specific heat of LPG (kJ/kg).

2.3.5 | Effectiveness factor

Effectiveness factor of the hybrid solar drying can be determined by dividing the drying rate of the said dryer by the drying rate of open-sun drying, as shown in Equation (7) (Dhanushkodi et al., 2014):

$$\text{Effectiveness factor} = \frac{\textit{drying rate of hybrid solar dryer}}{\textit{drying rate of open sun drying}} \tag{7}$$

TABLE 3 Uncertainty values in the measurement devices

No	Measurement device	Measured parameter	Accuracy	Uncertainty (%)
1	Digital weigher	Intial weight of vermicelli	± 0.1 g	± 0.2
2	Solar power meter	Solar intensity	± 0.1 W/m^2	± 1.7
3	Temperature and relative humidity meter	Ambient temperature Ambient relative humidity	± 0.01°C ± 0.01%	± 0.42 ± 0.23
4	Anemometer	Air velocity	± 0.01 m/s	± 1.62
5	Multimeter	Blower's voltage Blower's electric current	± 0.1 V ± 0.1 A	± 1.5 ± 0.8

2.3.6 | Energy utilization ratio

The value of the energy-utilization ratio (EUR) of the hybrid solar drying was determined using Equation (8) (Aviara, Onuoha, Falola & Igbeka, 2014):

$$EUR = \frac{M_a\,(h_{ai} - h_{ao})}{M_a\,(h_{ai} - h_{a\infty})} \tag{8}$$

where M_a denotes the mass flow rate (kg/s), h_{ai} the enthalpy of drying air entering the dryer (J/kg), h_{ao} the enthalpy of drying air exiting the dryer (J/kg), and $h_{a\infty}$ the enthalpy of ambient air (J/kg). Equation (9) can be used to determine the mass flow rate of drying air:

$$M_a = \rho_a V_a \tag{9}$$

where ρ_a denotes the dry-air density (kg/m^3) and V_a the volumetric rate of drying air (m^3/s). The enthalpy of drying air (inlet or outlet) can be determined using Equation (10):

$$h = C_{pda} T_{da} + W h_{sat} \tag{10}$$

where C_{pda} denotes the specific heat of drying air (kJ/kg °C), T_{da} the temperature of the drying air (°C), W the humidity ratio of the drying air (kg H_2O/kg dry air), and h_{sat} the enthalpy of saturated vapor (kJ/kg). The value of C_{pda} can be calculated using Equation (11):

$$C_{pda} = 1.0029 + 5.4 \times 10^{-5} T_{da} \tag{11}$$

2.3.7 | Exergy analysis

Unlike energy analysis, which only considers the first law of thermodynamics, exergy analysis is based on the second law. Equations (12) and (13) show the calculation of exergy entering (EX_i) and exiting the dryer (EX_o), respectively, in kJ/s (Badescu, 2017):

$$EX_i = M_a.C_{pda,i}.T_\infty \left[(T_{ai} - T_\infty) - \left(T_\infty \ln \frac{T_{ai}}{T_\infty} \right) \right] \tag{12}$$

$$EX_o = M_a.C_{pda,o}.T_\infty \left[(T_{ao} - T_\infty) - \left(T_\infty \ln \frac{T_{ao}}{T_\infty} \right) \right] \tag{13}$$

where T_{ai} and T_{ao} denote the drying-air temperature entering and exiting the dryer (°C), respectively, $C_{pda,i}$ and $C_{pda,o}$ denote the heat capacity of drying air entering and exiting the dryer (kJ/kg.°C) whereas T_∞ denotes the ambient temperature (°C). Equation (14) shows the relation between exergy loss (EX_L), exergy inflow, and exergy outflow during the drying process:

$$EX_L = EX_i - EX_o \tag{14}$$

Exergy efficiency (η_{EX}, %) is defined as the ratio between exergy exiting the dryer and the exergy entering the dryer, as shown in Equation (15) (Dincer & Rosen, 2007):

$$\eta_{EX} = \frac{EX_o}{EX_i} \times 100 \tag{15}$$

The exergetic improvement potential (IP, kJ/s) can be obtained with Equation (16) (Aviara et al., 2014):

$$IP = (1 - \eta_{EX})(EX_i - EX_o) \tag{16}$$

2.3.8 | Scanning electron microscope and electron diffraction X-Ray analysis

Dried vermicelli sample was tested using scanning electron microscope (SEM) and electron diffraction X-ray (EDX) to determine the microstructure images and chemical compounds contained in the sugar-palm vermicelli (Li, Liu, Shen, Zheng, & Tan, 2008).

2.3.9 | Proximate analysis

Proximate analysis can be used to represent the gross components of a food product. In this study, three proximate components, namely, fat, protein, and ash content, were analyzed. The fat content was determined using a Soxhlet extractor with n-hexane as the organic solvent. Protein content was analyzed using the Kjeldahl method, where the protein content can be determined by multiplying the total nitrogen by a factor. The ash content was calculated based on the weight of ash formed during sample combustion in the furnace at 550 ± 5°C (Greenfield & Southgate, 2003). The proximate analysis was conducted at the Integrated Laboratory of Diponegoro University.

2.3.10 | Color analysis

Color analysis was carried out using the Chromameter Minolta CR 300 (Minolta Camera Co., Japan), No 82281029). The device measured the parameters, L, a, and b; they were recorded on the paper sheet. All measurements were conducted three times and average values were taken. The L value represents brightness, with the values ranging from 0 (black) to 100 (white); a value represents the reflected light, which produces a red–green chromatic-color mixture with a positive value from 0 to 100 for red and a negative value from 0 to −80 for green; b value denotes the chromatic color of the blue–yellow mixture with the values ranging from 0 to 70 for yellow and 0 to −70 for blue (Hossain, Amer, & Gottschalk, 2008).

3 | RESULTS AND DISCUSSION

3.1 | Moisture-content analysis

Figure 3 shows the moisture content variations of vermicelli using open sun drying, natural solar drying, and hybrid solar drying (HSD) at

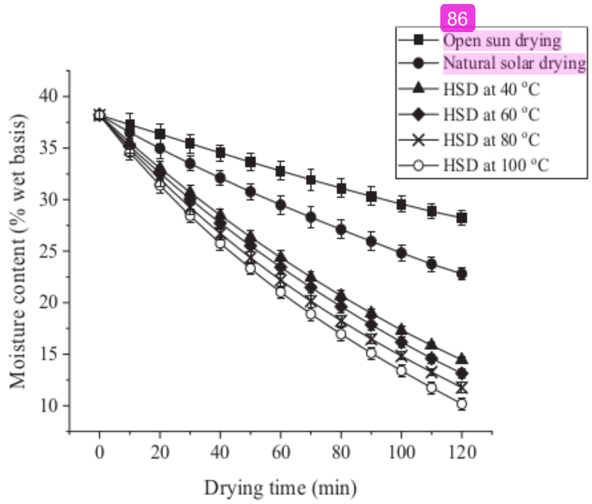

FIGURE 3 Moisture-content curve of vermicelli for different drying modes

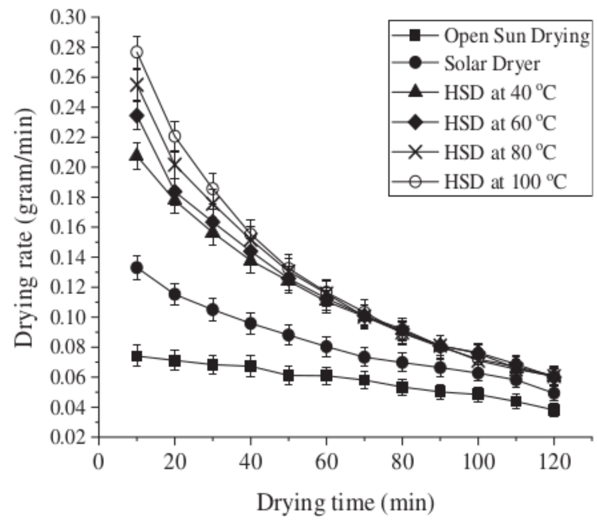

FIGURE 4 Drying-rate curve of vermicelli for different drying modes

40, 60, 80, and 100°C. For hybrid solar drying, the moisture content data obtained from all drying trays for each drying temperatures were calculated and the average value were taken. The final moisture content of vermicelli dried using open sun drying method and natural solar drying is 28.22 and 22.8%, respectively, whereas the final moisture content using hybrid solar drying at 40, 60, 80, and 100°C is 14.44, 13.14, 11.76, and 10.18%. Based on these results, hybrid solar drying at 100°C is the fastest while open sun drying method is the slowest. With 2 hr of drying time, hybrid solar dryer is able to reduce vermicelli's moisture content to the safe limit, which is 14.5% wet basis (Indonesian National Standard, 1995), whereas open sun drying and natural solar drying method are not able to do so. It can be seen from Figure 3 that significant differences exist with respect to reductions in the moisture content using the hybrid solar drying compared with the open-sun and natural solar-dryer methods. This is because the addition of LPG causes the dryer to gain more heat, resulting in faster drying (Murali, Amulya, Alfiya, Delfiya, & Samuel, 2020). During hybrid solar drying, it is evident that using a high temperature increases moisture reduction (Gupta, Cox, & Abu-Ghannam, 2011). In essence, increasing the temperature enhances moisture evaporation since it increases the heat transfer between the vermicelli and drying air; therefore, moisture removal from the vermicelli increases (Alara, Abdurahman, & Olalere, 2019; López-Vidaña et al., 2019).

3.2 | Drying-rate analysis

Figure 4 shows the drying-rate curve of vermicelli drying for open sun drying, natural solar drying, and hybrid solar drying (HSD) at different temperatures. The average drying rate (in gram/min) during open sun drying method, natural solar drying, and hybrid solar drying at 40, 60, 80, and 100°C is 0.058 ± 0.0058, 0.083 ± 0.0064, 0.116 ± 0.007, 0.120 ± 0.0075, 0.125 ± 0.0079, and 0.130 ± 0.0085, respectively. It is evident that using high temperatures increases the drying rate, with hybrid solar drying at 100°C being the fastest and open-sun drying being the slowest. At higher temperatures, the water movement from inside the vermicelli to the surface increases, which, in turn, increases the evaporation and the drying rate (Djaeni & Sari, 2015). The drying-rate curve also suggests that the drying rate during open-sun drying decreases linearly, while during natural solar drying, and hybrid solar drying at 40, 60, 80, and 100°C exhibits an exponential decrease. In all drying modes, the drying rate is the highest at the start of drying, decreasing continuously as drying progresses. This indicates that vermicelli drying takes place at the falling-rate period and that vermicelli drying is mainly controlled by diffusion (Dissa, Bathiebo, Desmorieux, Coulibaly, & Koulidiati, 2011; Khama, Aissani, & Alkama, 2016; Zhu, Liu, Wu, et al., 2015). A high drying rate during the initial period of drying can be attributed to the large difference between the moisture content of the vermicelli and the equilibrium moisture content of drying air, which causes the free moisture content of vermicelli to evaporate quickly (Balzarini, Reinheimer, Ciappini, & Scenna, 2018). As drying progresses, the amount of free moisture content reduces, leaving bound moisture content to be evaporated, which is located inside the internal tissue of the vermicelli. Indeed, compared with free moisture, it is more difficult to evaporate bound moisture; accordingly, evaporating bound moisture slows down the drying process and gradually decreases the drying rate (Anum et al., 2017; Murali et al., 2020) Therefore, the drying time required to evaporate the bound moisture content is much longer compared with the free moisture content, as seen in Figure 4 during the latter part of the drying process (Karam, Petit, Zimmer, Baudelaire Djantou, & Scher, 2016).

3.3 | Collector-efficiency analysis

Figure 5 shows the profiles of solar radiation during the drying experiment. In the days where the drying experiments were conducted, the weather is sunny with only few clouds. The minimum and maximum solar radiation recorded is 530.5 W/m^2 during hybrid solar drying at 60°C and 1,076.4 W/m^2 during natural solar drying method. It is seen from the figure that the solar radiation increases gradually, with similar pattern for all drying variables. The value of solar radiation reaches high value during drying between 90 and 120 min (around 925.9 to 1,076.4 W/m^2), which is between 11.30 a.m. and 12.00 p.m. Figure 6 shows the average collector efficiency during all drying variables. The values of collector efficiency are in the range of 29.4 to 48.4%, with an average value of 37.2 ± 0.66%. The highest value of collector efficiencies were recorded during drying between 100 and 120 min, within the range of 43.9 to 48.4%. At this time, the solar radiation was at a maximum, as shown in Figure 5. This indicates that solar radiation greatly affects the value and pattern of the collector efficiency, in which both have the same pattern as shown in Figures 5 and 6. This phenomena can be found in other solar-dryer research (Azimi, Tavakoli, Beheshti, & Rahimi, 2012; Kabeel & Abdelgaied, 2016). The values of collector efficiency in this experiment are quite similar with other solar-dryer studies, for instance, 36% at max (Kabeel & Abdelgaied, 2016), 31.5% on average (Lingayat, Chandramohan, & VRK, 2017), 42% on average (Anyanwu et al., 2012), and 48,2% on average (Lakshmi et al., 2019) However, despite similar pattern between both solar radiation and collector efficiency, there are some fluctuations on collector efficiency. Aside from being influenced by solar radiation and ambient temperature, a possible reason behind the fluctuations of collector efficiency values is the low air-flow rate passing through the solar collector (Şevik, Aktaş, Dolgun, Arslan, & Tuncer, 2019). In this experiment, the ambient air flowed through nine holes at the bottom of the solar collector by natural convection. Collector efficiency consists of the ratio of useful heat flow rate entering the collector and the incident heat flow rate at the absorber (Imre, 2014). Therefore, a low air-flow rate results in decreasing collector efficiency (Dhanushkodi et al., 2014; Mokhtarian, Tavakolipour, & Kalbasi-Ashtari, 2016). A possible solution to this problem is to install fans at the air inlet of the solar collector which will increase the air-flow rate inside the collector and the collector efficiency.

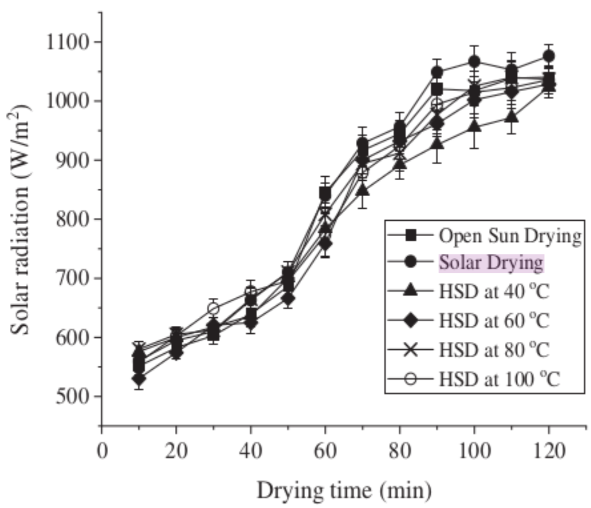

FIGURE 5 The profiles of solar radiation during the drying experiment

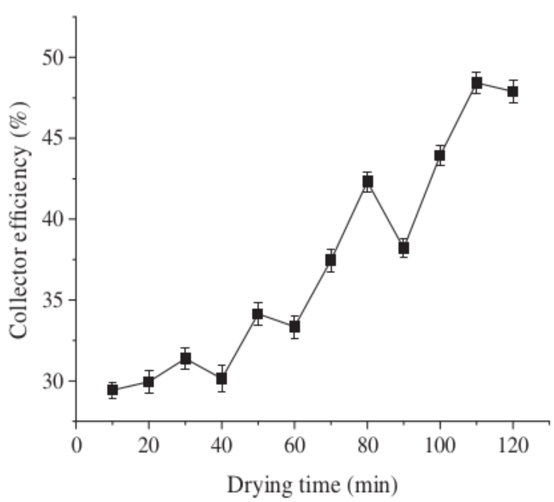

FIGURE 6 The profiles of average collector efficiency during drying experiment

3.4 | Dryer-efficiency analysis

Figure 7 shows the dryer-efficiency values for the hybrid solar-drying method at different temperatures. The dryer-efficiency value range during drying at 40, 60, 80, and 100°C is 5.5 to 31.9%, 6.2 to 45.2%, 6.1 to 47.9%, and 6.1 to 51.3%, respectively. Overall, the dryer efficiency for all drying temperatures ranges from 5.5 to 51.6%, which is

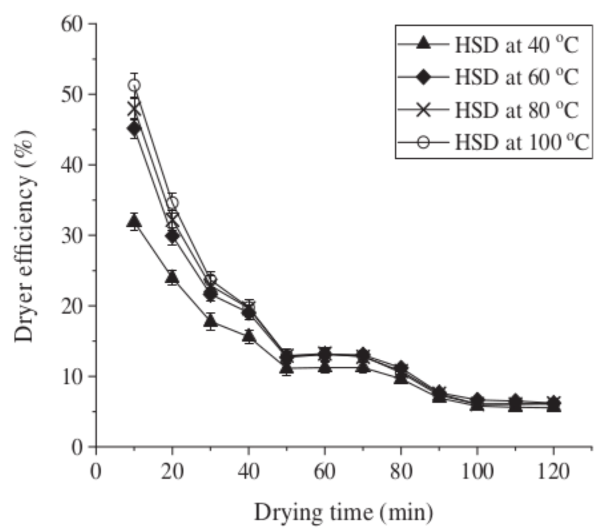

FIGURE 7 Dryer efficiency during hybrid solar drying at different temperatures

on a similar range with other solar dryer studies, such as 13.7 to 49.9% on solar dryer with heat pump (Yahya, Fudholi, Hafizh, & Sopian, 2016), 25 to 72% on a heat pump-assisted hybrid solar dryer (Mortezapour, Ghobadian, Minaei, & Khoshtaghaza, 2012) and 24.21 to 37.09% on hybrid solar dryer with LPG. It is evident from Figure 7 that, initially, the dryer efficiency is high for all drying temperatures; however, as drying continues, the dryer efficiency decreases gradually. Dryer efficiency decreases rapidly during the first 50 min of drying, then decreases slowly until the drying ends. Previously, it has been stated that vermicelli drying takes place at the falling-rate period. In this period, the drying rate starts decreasing due to increasing internal resistance to the moisture transport, which essentially slows down the evaporation of water. Dryer efficiency is defined as the ratio of energy used to evaporate water from vermicelli and energy supplied to the dryer. As the amount of water in the vermicelli decreases, the dryer efficiency also decreases (Ertekin & Firat, 2017; Strøm, 2011). Therefore, it is required to optimize this hybrid solar drying system to increase the dryer efficiency, especially during the later part of the drying experiment where drying becomes less efficient (around 5–6% efficiency value). Possible optimization method including adding a recovery dryer (Yassen & Al-Kayiem, 2016), using phase-change materials to help accumulate energy (Reyes, Mahn, & Vásquez, 2014), or recirculate the drying air exiting the drying chamber back into the drying chamber to reduce the energy consumption of the dryer (Mokhtarian et al., 2016).

Figure 8 shows the average values of dryer efficiency during hybrid solar drying at 40, 60, 80, and 100°C, which is 13.03 ± 0.52%, 16.07 ± 0.58%, 16.51 ± 0.63%, and 17.02 ± 0.7%, respectively. It is evident that the average dryer efficiency increases as drying temperature increases. When drying at high temperatures, the moisture uptake is fast due to the fact that there is reduced humidity in the drying air; therefore, the said air is able to carry more moisture. This result is similar to the results obtained by other solar-dryer studies (Abubakar, Umaru, Kaisan, et al., 2018; Mortezapour et al., 2012; Suherman, Djaeni, Wardhani, Dzaki, & Bagas, 2018).

3.5 | Effectiveness-factor analysis

Figure 9 shows the profile of the effectiveness factor for hybrid solar drying at different temperatures. The highest effectiveness factor was obtained during hybrid solar drying at 100°C in the first 10 min, with a value of 3.73. The average effectiveness factor of the hybrid solar-drying method at 40, 60, 80, and 100°C is 1.93 ± 0.11, 1.99 ± 0.13, 2.06 ± 0.14, and 2.13 ± 0.17, respectively. Indeed, the effectiveness factor increases when drying temperature increases. In addition, increasing the drying time decreases the effectiveness, which can be attributed to the reduced amounts of water evaporated from the material (Azimi et al., 2012). The effectiveness of the hybrid solar dryer is higher than one during the drying process, which indicates that the hybrid solar dryer is more effective than open-sun drying (Dhanushkodi et al., 2014). After drying for 100 min, the effectiveness factor is essentially constant for the rest of the drying process. Therefore, the effective drying time for vermicelli using the hybrid solar dryer is 100 min.

3.6 | Energy utilization ratio

3.6.1 | Energy-utilization ratio

Figure 10 shows the profiles of energy utilization ratio (*EUR*) during hybrid solar drying at different temperatures. The variations of *EUR* during drying at 40, 60, 80, and 100°C are 0.18 to 0.23, 0.22 to 0.25, 0.26 to 0.28, and 0.28 to 0.32, respectively. It is evident from Figure 9 that the values of *EUR* at all drying temperature are initially high,

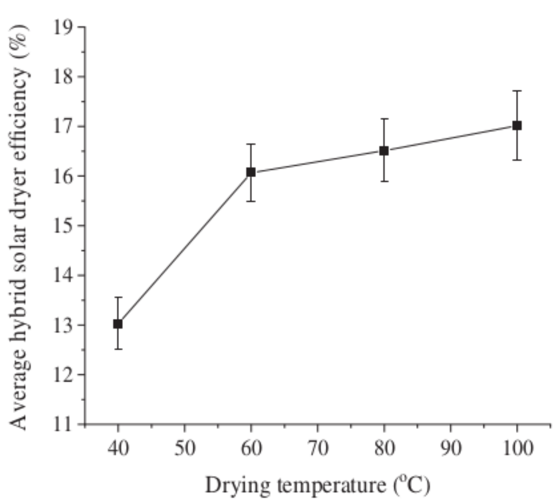

FIGURE 8 Average dryer efficiency during hybrid solar drying at different temperatures

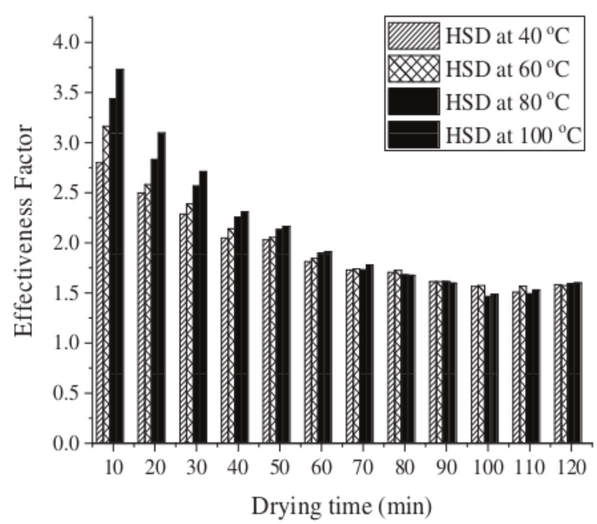

FIGURE 9 Profile of effectiveness factor during hybrid solar drying

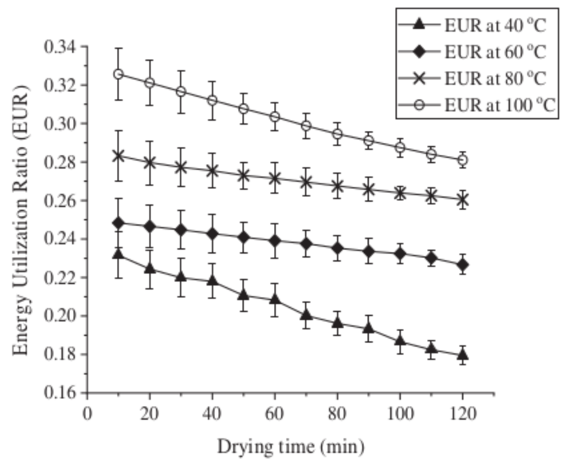

FIGURE 10 Profiles of EUR at different drying temperatures

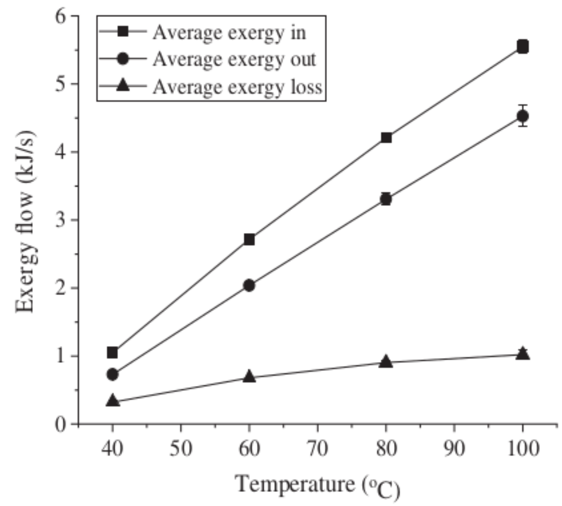

FIGURE 11 The profiles of average exergy inlet, exergy outlet, and exergy loss at different drying temperatures

then decrease over time, with hybrid solar drying at 40°C exhibit the fastest decrease. This phenomenon is also found on other food dryers, like fluidized bed dryer (Sarker et al., 2015) or pneumatic dryer (Suherman & Hidayati, 2018). At the beginning of the drying process, there is still a lot of water inside the vermicelli which causes the dryer to utilize more energy to evaporate the water (Akbulut & Durmuş, 2010; Sarker et al., 2015). As the water content of vermicelli decreases over time, the drying process becomes slower, which also reduces the energy utilization ratio because there is less water to be evaporated for the same energy input (Prommas, Rattanadecho, & Cholaseuk, 2010).

It can also be seen from Figure 10 that using higher drying temperature will increase the *EUR*. The increase of drying temperature will enhance the heat transfer between the drying air and the water inside vermicelli which will increase the moisture uptake and will utilize more energy (Yogendrasasidhar & Setty, 2018). However, the *EUR* values in this experiment are still lower compared to other studies, such as 0.27 to 0.45 on forced solar dryer for mulberry (Akbulut & Durmuş, 2010), 0.57 to 0.76 on solar dryer with recycle system for pistachio (Mokhtarian et al., 2016), or 0.6 to 0.65 on tray dryer for cassava starch (Aviara et al., 2014). Therefore, an optimization of the drying process is possible, for example, by recycling the drying air or increase the mass flow rate of drying air so that more energy will be utilized by the dryer.

3.7 | Exergy analyses

3.7.1 | Exergy inflow, exergy outflow, and exergy loss

Figure 11 shows the average values of exergy inflow, exergy outflow, and exergy loss at different drying temperatures for hybrid solar drying. Exergy inflow increases from 1.05 ± 0.033 to 5.55 ± 0.091 kJ/s when the drying temperature increases from 40 to 100°C. Similarly, exergy outlet increases from 0.73 ± 0.009 to 4.53 ± 0.15 kJ/s, whereas exergy losses increase from 0.3 ± 0.025 kJ/s at 40°C to 1.02 ± 0.067 kJ/s at 100°C. Overall, high drying temperatures increase the exergy flow in the dryer, including the exergy loss Similar patterns of exergy inflow, exergy outflow, and exergy loss can also be found on other exergy studies (Aviara et al., 2014; Chowdhury, Bala, & Haque, 2011; Sarker et al., 2015). When drying temperature increases, the water evaporation and energy utilization both increase (Boulemtafes-Boukadoum & Benzaoui, 2011; Şevik et al., 2019). At high temperatures, the mass- and heat-transfer rate both intensify, but also increases the entropy of the system, essentially increasing the irreversibility. The more irreversible a system is, the more exergy will be destroyed or lost. Destroyed exergy (or Exergy loss) represents the loss of quality and efficacy of the energy input (Beigi, Tohidi, & Torki-Harchegani, 2017; Dincer & Rosen, 2007).

3.7.2 | Exergy efficiency

Figure 12 shows the exergy-efficiency values during hybrid solar drying at different temperatures, which ranged from 67.4 to 71.8% at 40°C, 73.3 to 76.6% at 60°C, 76.9 to 80.3% at 80°C, and 79.1 to 83.6% at 100°C. It is evident that exergy efficiency increases when the drying temperature increases, although slight fluctuations do occur, most notably during drying at 40°C. As the drying temperature increased, more energy will be utilized by the dryer to evaporate water from vermicelli. This will also increase the exergy evaporation rate compared with the exergy rate of the inlet air, which increases the exergy efficiency (Beigi et al., 2017; Yogendrasasidhar & Setty, 2018). The fluctuations of exergy efficiency may be caused by exergy destruction in the drying chamber which reduces the amount of exergy utilized to evaporate water (Aghbashlo, Mobli, Rafiee, & Madadlou, 2012; Khanali, Aghbashlo, Rafiee, & Jafari, 2013).

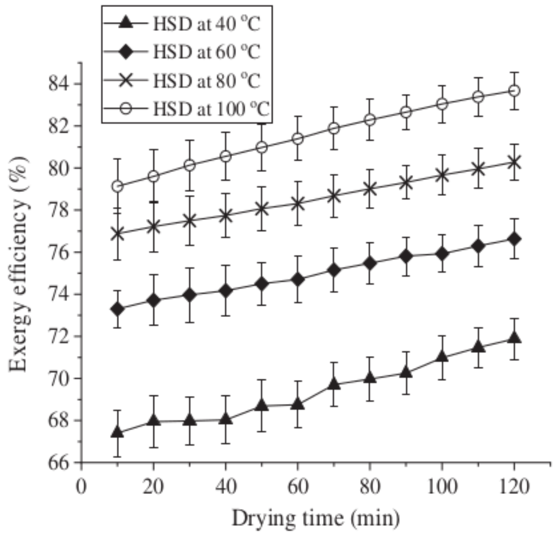

FIGURE 12 The values of average exergy efficiency at different drying temperatures

It is also evident from Figure 12 that exergy efficiency increases over time. During the early part of the drying, more heat will be consumed to evaporate water which increases the temperature difference between the inlet and outlet of the drying chamber, resulting in lower exergy efficiency. As drying progresses and water content inside vermicelli decreases, the temperature difference of the inlet and outlet also decreases. As a result, the value of exergy outflow will be closer to exergy inflow, essentially increasing the exergy efficiency (Karthikeyan & Murugavelh, 2018; Rabha, Muthukumar, & Somayaji, 2017). The value of exergy efficiency found in this experiment are roughly the same as other solar dryer studies. Ndukwu, Bennamoun, Abam, Eke, and Ukoha (2017) calculate the exergy efficiency between 66.79 to 96.09% on solar dryer with thermal storage. Karthikeyan and Murugavelh (2018) studied the forced-convection solar dryer applied for turmeric and found that exergy efficiency is in the range of 23.25 and 73.31%, while Şevik et al. (2019) calculate the exergy efficiency between 46.99 and 58.14% on solar-infrared dryer. It is evident that hybrid solar dryer is a viable method for vermicelli drying in terms of exergy efficiency.

3.7.3 | The improvement potential

Improvement Potential plays an important role in designing optimum solar-drying systems by minimizing the exergy loss (or irreversibilities) that occur during drying (Sansaniwal, Sharma, & Mathur, 2018). Figure 13 shows the average value of Improvement Potential of hybrid solar drying at 40, 60, 80, and 100°C, which is 0.098 ± 0.012 kJ/s, 0.17 ± 0.014 kJ/s, 0.193 ± 0.017 kJ/s, and 0.189 ± 0.028 kJ/s, respectively. It is evident that, as drying temperature increases, improvement potential (IP) increases (Aviara et al., 2014), with the exception during

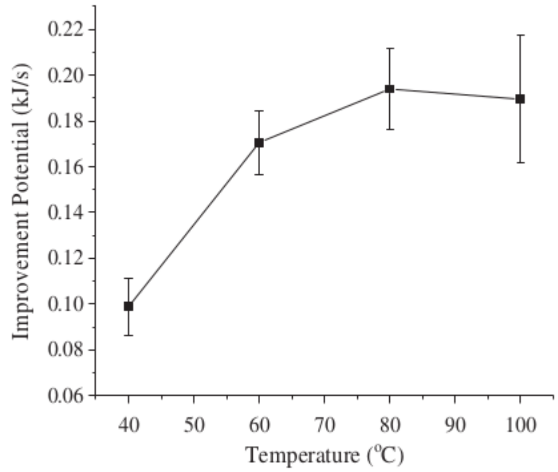

FIGURE 13 IP at different drying temperatures

drying at 100°C, in which the IP slightly decreases. Previously, it was found that exergy loss increases with an increase in drying temperature. Indeed, increased exergy loss indicates a possibility of improved dryer performance, which explains the increasing value of IP (Beigi et al., 2017; Sansaniwal et al., 2018). The slight decrease of IP found in this experiment may be caused by small increase of average exergy loss during drying from 80 to 100°C (as seen in Figure 10). The exergy efficiency values at 100°C are higher than 80°C which caused by faster reduction in temperature difference between inlet and outlet of the drying chamber. As a result, the value of exergy output becomes closer to exergy input and the amount of lost exergy will decrease, which may be the reason why there are not much exergy to be improved during drying at 100°C compared to drying at lower temperature. However, compared to the average exergy inflow, the values of improvement potential in this experiment are very low (accounting for only 3.4 to 9.4% of the average exergy inflow). This indicates that, although hybrid solar dryer is efficient in terms of exergy, it offers small potential on minimizing the exergy loss (Aghbashlo et al., 2012; Ndukwu et al., 2017).

3.8 | SEM–EDX analysis

For SEM–EDX analysis, the sample used was dried vermicelli at 100°C. Figures 14 and 15 show the cross-sections of vermicelli at different two locations. The cross-section holes ranged from 150 to 181 μm. After the starches were processed into the vermicelli, starch granules were not evident. This means that the starch granules are already damaged. It is evident from both Figures 14 and 15 that the structure of the vermicelli surface is rough, bumpy, and appears fractured. This is caused by high drying temperature and rapid drying which damages the vermicelli surface and affects the physical structure of the vermicelli (Alara et al., 2019). During rapid drying at high temperature, the rubbery part of the vermicelli's surface becomes glassy quickly, leaving the rubbery part inside the vermicelli structure.

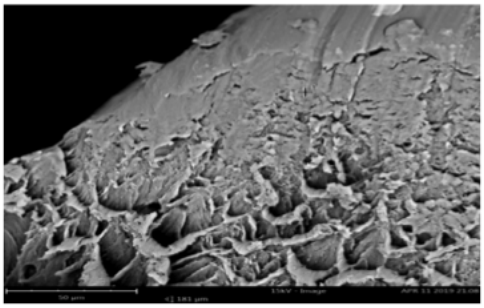

FIGURE 14 Cross-section of vermicelli (location 1)

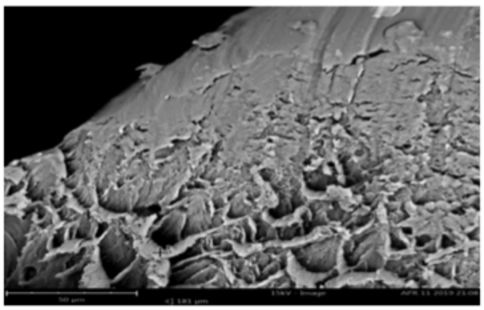

FIGURE 15 Cross-section of vermicelli (location 2)

This rubbery part will eventually shrink and collapse, resulting in rough and bumpy surface. In addition, due to fast drying process, the evaporated moisture from the vermicelli cannot be replaced in time by moisture diffusion from inside the vermicelli. This will damage the vermicelli surface and cause fractures along the surface, as seen in the Figures 14 and 15 (An et al., 2016; Xiang, Ye, Zhou, Wang, & Zhao, 2018).

Table 4 shows the chemical compounds of vermicelli dried at 100°C, from which it is evident that the vermicelli consists of carbon (40%), oxygen (34.7%), and nitrogen (25.3%). Carbon and oxygen compounds dominate due to the high amount of starch present in the sugar-palm vermicelli, which ranges from 25 to 50% (Manatar, Pontoh, & Runtuwene, 2012).

3.9 | Proximate analysis

Only vermicelli samples during hybrid solar drying were subjected to proximate analysis. The average fat and protein content obtained was 1.23 and 3.175%, respectively. The fat and protein content of raw sugar-palm starch, according to the Indonesian National Standard, is 0.18 and 0.49%, respectively (Suherman & Hidayati, 2018). Accordingly, the results indicate that there is an increase in fat and protein content when processing the sugar-palm starch into dry vermicelli. This is because, during the drying process, there is significant moisture removal, which increases the concentration of other nutrients (Uribe et al., 2017). Therefore, hybrid solar drying is able to increase the content of other nutrients in addition to reducing the moisture content of vermicelli.

Table 5 shows the vermicelli ash content after the drying process, from which it is evident that the ash content at 40, 60, and 80°C is in accordance with Indonesian standards, which is 0.5% max (Indonesian National Standard, 1995). However, hybrid solar drying at 100°C results in a high ash content of vermicelli. Since drying at high temperatures rapidly evaporates the water, the minerals may not be carried by the drying air at all; in other words, the ash content increases in the vermicelli samples (Nielsen, 2010).

3.10 | Color analysis

Table 6 shows the value of color parameters of vermicelli during hybrid solar drying, from which it is evident that, compared with open-sun drying, *L* decreases at higher temperatures. In contrast, *a* and *b* increase when vermicelli is dried at high temperatures. Moreover, the hybrid solar drying results in the vermicelli taking on a reddish–yellowish color, which can be attributed to starch oxidation due to heat and solar-radiation exposure (Díaz, Dini, Viña, & García, 2018). Regarding color, *L* is important for vermicelli since bright/clear vermicelli is associated with good quality. Reductions in *L*, or brightness in the vermicelli, during drying can be attributed to a browning reaction, especially the Maillard reaction, which is the reaction between amino acids and reduced sugars that is accelerated at high temperatures (Tumpanuvatr, Jittanit, & Surojanametakul, 2018).

TABLE 4 Chemical compounds in dried vermicelli

Compound	Weight concentration (%)	Error (%)
Carbon	40.0	1.4
Oxygen	34.7	1.0
Nitrogen	25.3	1.1

TABLE 5 Ash content of dried vermicelli

Drying temperature (°C)	Ash content (%)
40	0.233
60	0.100
80	0.230
100	0.860

TABLE 6 Color parameters of vermicelli dried at different temperatures

Drying temperature (°C)	L	a	b
40	87.2	−9.83	0.6
60	82.56	−9.36	2.76
80	82.46	−8.8	−0.76
100	82.5	−7.6	0.4
Open-sun drying	88.3	−10.2	−1.5

4 | CONCLUSIONS

In this study, sugar-palm vermicelli drying was examined using a Hybrid Solar Dryer (HSD). The results suggest that the hybrid solar dryer is faster than both open-sun drying and natural solar drying. The final moisture content of vermicelli dried using open-sun drying, natural solar drying, and hybrid solar dryer at 40, 60, 80, and 100°C is 28.22, 22.8, 14.44, 13.14, 11.76, and 10.18%, respectively. From the drying-rate analysis, it is evident that vermicelli drying takes place at the falling-rate period, which is indicated by the decreasing drying rate over time. Overall, using a hybrid solar dryer at 40 to 100°C increases dryer efficiency (from 13.02 to 17.02%), Energy Utilization Ratio (EUR) (from 0.18 to 0.32) and exergy efficiency (from 67.4 to 83.6%). Exergy analysis suggests that exergy inflow, exergy outflow, and exergy loss increase with increase in drying temperature. However, hybrid solar dryer offers small potential on minimizing the exergy loss. During hybrid solar drying, the proximate components essentially do not change; moreover, the color analysis suggests that drying alters the color of the vermicelli and that using high temperatures decreases whiteness value from 87.2 to 82.5. In addition, drying at 100°C results in the worst vermicelli quality and also cause damage and fractures at the vermicelli surface, as evident from the *SEM* analysis. Indeed, hybrid solar drying is a viable option for sugar-palm vermicelli drying, since it ensures a fast-drying time and acceptable quality. However, it is not without its own limitations, such as reduction in the brightness of dry vermicelli and degradation at the surface of the vermicelli, particularly due to rapid drying at 100°C. Therefore, further development and optimization of the hybrid solar drying are required to improve overall performance.

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CONFLICT OF INTERESTS

The authors declared no potential conflicts of interests with respect to the research, authorship, and publication of this article.

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