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Techno-economic Analysis of a Hybrid Solar Dryer with a Vacuum Tube Collector for Hibiscus Cannabinus L Fiber

A. S. A. Hamid[1,2], A. Ibrahim[2‡], J. Assadeg[2,3], E. Z. Ahmad[2,4], K. Sopian[2]

[1]Faculty of Science and Natural Resources, Universiti Malaysia Sabah, 88400 Kota Kinabalu Sabah, Malaysia.

[2]Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi Selangor, Malaysia.

[3]Department of Renewable Energy Engineering, Faculty of Energy and Mining, Sebha University, P.O. Box 18758, Libya.

[4]Faculty of Electric and Electronic Engineering Technology, Universiti Teknikal Malaysia Melaka, 76100 Melaka, Malaysia.

(pian@ums.edu.my, iadnan@ukm.edu.my, jassadeg@gmail.com, emyzairah@utem.edu.my, ksopian@ukm.edu.my)

‡ Corresponding Author; A. Ibrahim, Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi Selangor, Malaysia, Tel: +603 89118572, Fax: +903 89118574, iadnan@ukm.edu.my.

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Abstract- Solar energy is one of several types of renewable energy and has numerous applications. Types of solar energy include photovoltaic, thermal, and thermophotovoltaic modes. Drying is an application of thermal solar energy which is used to remove water from a sample. The main reason this study was done was due to the lack of use of hybrid solar dryers for high load kenaf fibers. This dryer is capable of extracting water from the sample with a maximum load of up to 1400 kg. This study aims to evaluate certain open drying methods as compared with modern thermal drying methods. The dried samples were a type of natural fiber commonly known as kenaf (*Hibiscus Cannabinus L*). The test amounts were 175 kg and 1400 kg, respectively. The solar thermal drying uses several components, including an evacuated tube collector, water storage tank, heater, air intake, pump, and a drying chamber. The parameters to be measured included weight, water content, time, and electricity usage. Dryer performance was evaluated in terms of water extraction rate, exact water extraction rate, specific energy usage, dryer operational costs, and specific operational costs. The results of the evaluations indicate that drying with the maximum load of 1400 kg increased the extracted water, exact water extraction rate, and dryer operational costs by 97.27 kg/hour, 39.86 kg/kWh, and 3.72 Malaysian ringgit (approximately 0.90 USD), respectively. Specific energy consumption and specific operating costs fell by 0.10 kWh/kg and 0.05 RM/kg (0.012 USD/kg), respectively. Based on these findings, economic analysis was carried out to estimate the profitability and frequency of drying. The results indicate that a maximum load of 1400 kg is superior to the open drying method, with an annual yield and return of investment period of RM 64992 (15,723 USD) and 3.7 years, respectively.

Keywords- Thermal drying, thermal solar energy, natural fiber, kenaf fiber, hibiscus cannabinus L.

1. Introduction

Solar energy is a type of renewable energy which includes photovoltaic, thermal, and thermophotovoltaic modes. Photovoltaic technology converts radiation spectra from the sun into electric. In comparison, thermal solar energy directly uses heat from the sun, such as in a drying process. Combining photovoltaic and thermal modes using thermophotovoltaic technology harnesses the benefits of both methods, allowing for the simultaneous production of both heat and electrical energy [1]. However, the criteria for evaluating the performance of a thermal system differ from those of a photovoltaic system. In general, the output of a photovoltaic system decreases as the collector temperature increases [2]. Conversely, the performance of a thermal system generally increases with temperature, but there are limits to such gains.

Thermal drying is one application of solar energy. The collector absorbs heat from certain wavelengths of the sun's rays. The thermal drying itself employs air or fluid as a heat transfer medium. Thermal drying methods are divided into three types: passive, active, and hybrid [3]. Passive thermal drying or natural convection is the simplest of the three. A passive dryer studied by Othieno [4] is a small heat box measuring 2 m × 1 m. The sides and bottom are easily moved and can be made of either wood or metal. Transparent polyethylene is used as a cover. There are numerous holes in the side which serve for ventilation [4].

Active thermal drying or forced evaporation is a method which uses a fan or blower to generate airflow within a dryer. Al-Juamily et al. [5] built and tested an indirect forced air dryer to dry fruits and vegetables in Iraq. This thermal dryer includes a solar collector, blower, and drying cabinet. The dual solar collectors each have a v-groove air intake. The collector has a single-layer glass cover. The overall absorption area is 2.4 square meters. The drying cabinet is 1 m wide, 0.33 m thick and 2 m high. The cabinet is divided into six sections by five racks. The walls of the drying chamber are aluminum, except for the side facing south, which is a glass plate which is 1 m wide, 2 m long and 0.002 m thick [5].

Hybrid thermal drying uses an additional heat source which can increase or maintain a drying temperature. There are seven types of hybrid dryers, as summarized in Table 1.

Table 1. Overview of Thermal Drying Types

Source	Hybrid Dryer Type	Description
[6,7]	Dryer system with heat storage	This system uses water and stones to store heat. Drying time is thus shortened. It may also be used to produce hot water when the dryer is not in use.
[8,9]	Dryer system with added units	This mixed-mode thermal drying system with multiple shelves uses an additional electric heater. A study showed that the system shortened drying time by 1.8 to 2.2 times.
[10]	Hybrid system using geothermal source or wastewater	This system is used to dry fruits and vegetables. The dryer offers a return of investment period of 2.4 years. Geothermally heated water allows the system to maintain a drying temperature of up to 60˚C both day and night.
[11]	Photovoltaic dryer system	This is a photovoltaic dryer system with the ability to operate continuously for up to two weeks. Testing showed that 31 % and 29 % levels of energy savings were recorded when drying coconut and cocoa, respectively.
[12]	Dyer system with heat pump	A study of steam collectors and air collectors was conducted in Singapore. The results showed that the efficiency of the vapor collector increased commensurately with increased refrigerant flow rate. Maximum vapor collector and air collector efficiency levels were 86 % and 75 %, respectively.
[13]	Dryer system with chemical heat pump	This system uses the following reaction (salt and gas): $CaCl_2.2NH_3 + 6NH_3 \rightarrow CaCl_2.8NH_3 + 6\Delta Hr$ The reaction between the ammonia gas and solids releases heat, which is used to heat the air for drying.
[14]	Solar dryer system with dehumidifier	This system is used to dry medicinal herbs. It produces dry heat and is suitable for low temperature drying. The humidity and temperature of the drying chamber are 40 % and 35℃, respectively.

The hybrid dryer is an advanced system equipped with various additional components and resources. The operation also more dynamic to achieve optimal drying. However almost all these dryers have a low drying load capacity. This condition gives an advantage to the dryer in this study which has a maximum load of 1400 kg. The dryer specially designed to operate on a large scale to meet the needs of the agricultural industry. Tests that have been performed on natural fibers. The fibers have great potential to replace artificial fibers in various industries

The natural fiber used in these drying tests was derived from Hibiscus Cannabinus L, commonly known as kenaf [15,16]. Kenaf is Malaysia's third most common commodity crop, after oil palm and rubber. A kenaf plantation is operated by the National Kenaf and Tobacco Board (NKTB). Kenaf research is conducted by Malaysian Agricultural Research and Development Institute (MARDI) and Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia. Figure ~~3~~ 1 shows a kenaf plant in Chuping, Perlis.

Kenaf fiber undergoes several steps to becoming long fibers, including harvesting [17], separation [18], retting [19], drying [20], and storage. Harvesting is performed with a harvesting machine when the kenaf plant reaches maturity at 3 – 5 meters in height. The separation machine is used to separate the core of the kenaf shaft from the exterior, which then undergoes a retting process to separate the long fibers from impurities. The fibers are then dried and stored for sale.

Fig. 1. Kenaf plant

2. Research methods

2.1. Solar Thermal Drying

Potential solar energy in Malaysia is very high, with a maximum solar intensity of greater than 1000 W/m^2 and an average value of around 500 W/m^2 [21]. The hybrid thermal drying used in this test was measured at Chuping, Perlis, Malaysia, with coordinates 6°33'09"N 100°16'58"E. Chuping is a 'hotspot' in the state of Perlis, making it advantageous to employ solar energy there. Numerous studies have been conducted in Perlis with positive results [22 – 25].

The components used in this evaluation were an evacuated tube collector, water storage tank, heater, air handler, pump, and drying chamber. The evacuated tube collector functioned to absorb solar energy and transfer it into water in the form of thermal energy. The total area of the collector was 48.45 m^2. The heat energy which was produced was drained into and stored in a tank with a capacity of 1200 liters. The tank's walls were insulated to prevent the loss of heat. There was a total of six heating units with a power of 9 kW per unit. The air handler served to intake ambient air using a blower motor, heat the air by moving it into a heat exchanger, then blow the heated air into the drying chamber. The pump was used to transfer heat by circulating water between components. Pump-1 moved water between the collector and the tank. Pump-2 in turn moves water between the tank and the air handler. The drying chamber was where drying took place. The fiber was hung inside, and hot air was channeled during the drying process. The chamber had an area of 16.8 m × 3.5 m, with a concrete cement floor, and was covered with transparent polycarbonate. Figure 2 provides illustrations and technical sketches of the solar thermal dryer.

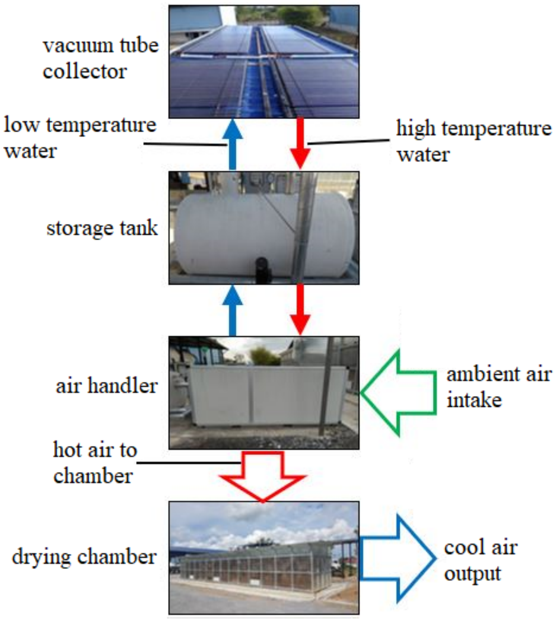

Fig. 2. Illustration of the solar thermal dryer for kenaf fiber

2.2. Data Gathering

The thermal and open drying methods were compared. The dryer was tested for two loads of kenaf fiber: with 175 kg, known as test A and 1400 kg, known as test B. The value of wet kenaf is the result of several previous processes. Each of these processes has limitations in terms of harvesting ability, transport, and handling of the retting process. Based on the annual report by National Kenaf and Tobacco [26] and on-site observations, it is found that the significant value of the load produced is 175 kg and 1400 kg. Kenaf was hung parallel to the length of the drying chamber. The parameters in Table 2 were recorded before and after the drying process.

Table 2. Measured parameters

Parameter	Symbol	Unit
Fiber weight	W	kg
Drying time	t	hr
Gross moisture content	MC w.b	%
Electricity consumption	E	kWh

Weight was measured using a digital scale with a maximum load of 300 kg and an accuracy of ±0.1 kg. Drying time was recorded on a digital timer. Water content was measured using the oven technique. Each sample was heated at a temperature of 100℃ for 24 hours to obtain the weight of the dry solids. Energy consumption was measured using a kilowatt-hour meter. The meter had an accuracy of 0.1 kWh and an accuracy range of ±0.05 kWh. Electricity costs were estimated by referring to the electricity tariffs of Malaysia's National Energy Corporation at 0.390 RM/kWh (0.094 USD/kWh) for the first 200 kWh and 0.472 RM/kWh (0.11 USD/kWh) for each additional kilowatt-hour. Figure 3 shows the kenaf fibers hung in the chamber for drying

Fig. 3. Kenaf fibers in the drying chamber

2.3. Dryer Performance

The performance of the dryer for both loads was evaluated in terms of several indicators, including Water Extraction Rate WER, Exact Water Extraction Rate EWER, Specific Energy Usage SEU, Dryer Operational Costs DOC, and Specific

Operational Costs SOC. The calculations for these performance indicator values are shown in Table 3.

Table 3. Calculations for thermal drying performance indicators

Performance indicator	Equation	Unit	Equation number
WER	$(w_i - w_f)/t$	kg/hr	(1)
EWER	$(w_i - w_f)/Q$	kg/kWh	(2)
SEU	$Q/(w_i - w_f)$	kWh/kg	(3)
DOC	C_Q/n	RM	(4)
SOC	C_Q/w_f	RM/kg	(5)

Where w_i = initial weight, w_f = final weight, t = drying time, Q = electricity consumption, C_Q = electricity cost, and n = number of drying cycles.

2.4. *Economic Analysis*

Economic analysis has been performed in terms of the performance indicators described above. The aspects considered included profit, annual return on investment, and Return of Investment ROI period. The results of the analysis are focused on the difference in the ROI period of the thermal drying method as compared to the open drying method. Annual Profit AP values were determined by using Eq. (6) or (7).

$$AP = F[C_d.w_d - (C_w.w_w + Q.T_e)] \qquad (6)$$

or

$$AP = F\left[C_d.w_d - \left(C_w.w_w + SOC.w_f\right)\right] \qquad (7)$$

Where F = annual drying frequency, C_d = dry kenaf price, w_d = dry kenaf weight, C_w = wet kenaf price, w_w = wet kenaf weight, and T_e = electric tariffs. The return on investment (ROI) period was calculated by using Eq. (8).

$$ROI = capital\ costs/annual\ revenue \qquad (8)$$

3. Results and Discussion

The drying tests resulted in final weights of 64.4 kg and 316.0 kg for tests A (175 kg) and B (1400 kg), respectively. The details for each parameter are shown in Table 4, and drying performance indicators are shown in Table 5.

Table 4. Detail parameter values

Parameter	Test A (175 kg)			Test B (1400 kg)		
	Before	After	Difference	Before	After	Difference
Weight, w	175.0 kg	64.4 kg	110.6 kg	1400 kg	316 kg	1084 kg
Drying time, t	-	-	5.25 hr	-	-	9.16 hr
Water content, $MC\ w.b$	100 %	36.8 %	63.2 %	100 %	22.57 %	77.43 %
Electricity usage, E	892.25 kWh	905.05 kWh	12.80 kWh	905.45 kWh	927.80 kWh	22.35 kWh

Table 5. Dryer performance indicators for tests A and B

Performance indicators	Test A (175 kg)	Test B (1400 kg)	Difference (B – A)	Unit
WER	21.07	118.34	97.27	kg/hr
EWER	8.64	48.50	39.86	kg/kWh
SEU	0.12	0.02	-0.10	kWh/kg
DOC	5.00	8.72	3.72	RM
SOC	0.078	0.028	-0.050	RM/kg

Test B showed a higher weight reduction at 1084 kg. Drying time also increased by 9.16 hr (2 days) as compared to test A at only 5.25 hr (1 day). Time and the number of drying days are important, as they impact the AP and ROI period. Electricity consumption for test B was higher at 22.35 kWh as compared to test A at 12.50 kWh. Energy consumption affects the performance of the dryer in terms of cost. The test indicates that more time and energy are required to dry a larger fibre load.

Significant differences were found in the performance indicators of tests A and B. The increases in the values of the WER, EWER, and DOC reached 97.27 kg/hour, 39.86 kg/kWh and 3.72 RM, respectively. Decreases were recorded for SEU and SOC of 0.10 kWh/kg and 0.050 RM/kg (0.012 USD/kg), respectively. The values for the WER and DOC were proportional to the size of the load or dryer, with a larger load giving higher values. As the values of the EWER, SEU, and SOC are dependent on amounts of energy or weight, these values may be used to compare thermal drying methods.

Economic analysis has been based on a capital cost of RM 240000 (57,870 USD). The prices of wet and dry kenaf were RM 300 (72.34 USD) and RM 3500 (843.98 USD) per ton [26,27]. A comparison of thermal drying with the open drying method has been performed for load tests A and B. The findings for tests A and B are shown in Table 6 and 7, respectively.

Table 6. Comparative results for test A (175 kg)

	Open drying	**Solar thermal drying**
Drying and kenaf costs	RM 52.5	RM 57.5
Drying weight	64.4 kg	64.4 kg
Drying result	RM 172.9	RM 167.9
Number of annual drying cycles	48	144
Annual weights	3091.2 kg	9273.6 kg
Annual revenue	RM 8299	RM 24177
Return on investment	28.9 years	9.9 years

Table 7. Comparative results for Test B (1400 kg)

	Open drying	**Solar thermal drying**
Drying and kenaf costs	RM 420.0	RM 428.7
Drying weight	316 kg	316 kg
Drying result	RM 686	RM 677
Number of annual drying cycles	24	96
Annual weights	7584 kg	30336 kg
Annual revenue	RM 16464	RM 64992
Return on Investment	14.6 years	3.7 years

The results shown in Table 6 and 7 indicate that the costs for drying and kenaf are low for the open drying method. The final weights for both tests were the same at 64.4 kg and 316 kg, respectively. A significant difference is noted between the drying frequencies for each method. Solar thermal drying allowed for higher drying frequencies at 114 for test A and 96 for test B. These frequencies are double the frequencies obtained for open drying, in turn decreasing the ROI period. Figure 4 shows the capital costs and increases on return on investment for the solar drying method in tests A and B, as well as the results for open drying for tests A and B.

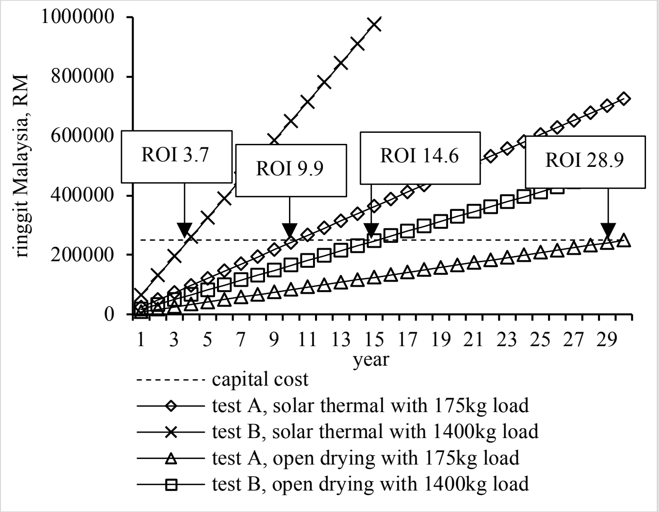

Fig. 4. Return on Investment (ROI) for each drying method for tests A (175 kg) and B (1400 kg)

The intersections shown in Fig. 3 indicate the value of the ROI period for each method used. The repayment periods for tests A (open), A (thermal), B (open) and B (thermal) were 28.9 years, 9.9 years, 14.6 years, and 3.7 years, respectively.

4. Conclusion

Tests of solar thermal drying were conducted with two different loads to test the performance of the dryer. Based on economic projections derived from their performances, test with load of 1400 kg required greater time and energy than test with load of 175 kg, translating into differences in water extraction rate and dryer operating costs. Performance indicators show an advantage for test with load of 1400 kg using solar thermal.

A comparison of the solar thermal drying method with the open drying method proves that the solar method with a load of 1400 kg was superior. Despite its higher costs for drying and kenaf, annual revenue and ROI period are also better at RM 64992 (15,683 USD) and 3.7 years, respectively.

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