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ENVIRONMENTAL-ECONOMIC ANALYSIS OF PORTABLE MIXED-MODE GREENHOUSE DRYER FOR FIG LEAVES

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***Abstract**. Energy and environomical analysis play important role in designing a solar thermal drying system as these analyses identify the high energy-consuming area, formulate energy-saving measures and evaluate the size of any potential savings. In this study, a greenhouse solar dryer with a double-pass multi-hollow collector for leaf drying was evaluated using environmental-economic analysis. Environmental analysis includes the determination of embodied energy, energy payback time (EPBT) period, as well as CO2 emissions per year, carbon mitigation and carbon credit. The embodied energy of a passive dryer is 606.86 kWh and EPBT of 16.68 years, while for an active dryer, the values are determined at 636.17 kWh and 10.39 years, respectively. CO2 emission for the passive dryer is 47.17 kg per year, net CO2 mitigation of 124.6 kg, and earned carbon credit of RM 2.58 – RM 12.38. The active dryer has CO_2 emission of 47.14 kg, net CO_2 mitigation of 594 kg, and earned carbon credit of RM 51.95 – RM 247.66. Economic analysis of this dryer shows that the energy cost associated with its operation ranges from RM 1.59 to RM 4.77, monthly.*

Keywords: renewable energy; solar energy; solar dryer; environmental analysis; economic analysis

1. Introduction

Renewable energy has gained much attention in the global quest of replacing dirty, non-renewable fossil fuels as an energy sources. Renewables are more environmentally friendly and cost-effective, as it releases less carbon footprint and greenhouse gas emissions, thus their power generation is much cleaner than fossil fuels. Among types of renewable energy, solar energy is identified as the most abundant with minimal impact on ecosystem, and is suitable for all types of applications, from small-rural scale to more complex, industrial scale. The application of direct solar energy can be divided into two categories; photovoltaic and thermal application. Solar photovoltaics uses semiconductor solar panels to convert sunlight into electrical energy. On the contrary, solar thermal technology harnesses the thermal capacity of sunlight for various applications; drying, heating, cooling, etc. For this research, solar thermal technology for agricultural drying will be the focus, using the application of a solar-assisted dryer system (Safri *et al.*, 2021), (Fudholi & Sopian, 2018b), (Fudholi & Sopian, 2018c).

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The use of solar-assisted dryer systems as a drying medium is the best option. Solar energy manipulation through the use of solar dryers significantly increases heat load, removes humidity from products, and preserves product quality. The most recent solar drying system application trends have been studied and reported. Solar drying has been used to successfully dry agricultural and marine products in Malaysia and Indonesia, including fruits and vegetables, fish, medicinal herbs, and oil palm (Hii *et al*., 2011), (Fudholi & Sopian, 2018a), (Yahya *et al*., 2018), (Yahya, 2016b), (Yahya *et al*., 2016a), (Desa *et al*., 2019).

More commonly, the leaves of *Ficus carica* L. trees are known as the fig tree, which is native to the Mediterranean and middle eastern origin. The tree is widely grown by cultivation as well as in the wild around the tropical and sub-tropical regions around the world. In Malaysia, the cultivation of fig trees has started to take off due to the recent realization of the numerous health benefits of its fruits and other components. Identified as one of the superfoods, the nutritional benefits of figs are not only limited to the fruits but also in other parts of the plant i.e. roots, latex and leaves. Traditionally, the fig plant has been known to be a remedy for diabetes, liver diseases, asthma, cough, ulcer, vomiting, menstrual pain, skin diseases, scabies and gonorrhoea (Badgujar *et al*., 2014). One of the most outstanding benefits of fig leaves is its strong antidiabetic properties. Deepa *et al*. (2017) reviewed the antidiabetic potential of Ficus species and concluded high presence of bioactive metabolites and antioxidants in fig leaves which contributes to its efficiency mechanism in regulating glucose level. To fully benefit from the antidiabetic properties of the fig components, leaves decoction is a common way of consumption among patients. Traditional uses for fig tree leaves include the prevention of nutritional anaemia, the treatment of tumours and inflammatory illnesses, and anthelmintic and antitumor properties. (Mahmoudi *et al*., 2016). According to additional sources, fig "leaf juice" is also used to cure scabies, earaches, toothaches, migraines, ear and toothaches, sexual abnormalities, diarrhoea, haematuria, and asthma. (Mahmoudi *et al*., 2016). Hence the importance of drying of fig leaves is to produce fig leaf tea, which can preserve the leaves for extended consumption without compromising its nutritional content. This study focusses on the evaluation of portable mixed mode greenhouse dryer for fig leaves by using environmental-economic analysis.

2. Methods

In this research, portable mixed mode greenhouse dryer consists of 3 main components; double-pass multi-hollow collector, drying chamber and ventilation as shown in Figure 1. This dryer's design also considers mobility; as a result, wheels were added to make transportation easier.

The solar collector employed in this dryer is a double-pass collector, meaning that the air entering it will pass through both an upper and a lower channel. The transparent window, solar absorber flat plate, and insulation layer make up the solar collector's parts. The specifications of solar collector components are given in Table 1. The drying chamber is the second unit of the entire greenhouse solar dryer system. Heated air leaving solar collector will travel through the opening i.e. air hole at the bottom of the collector, and then enters the drying chamber. Depending on the mode of air movement, drying air will either travel using natural buoyancy (passive mode), or ventilated using exhaust fans (active mode). To have greenhouse effects on drying samples, the walls of the dryer are constructed using transparent material.

In this research, acrylic was used as the material of construction. The drying chamber is equipped with a set of doors to facilitate samples in and out of the chamber, and also made from acrylic. To store food materials, a single perforated tray was installed in the middle of the chamber. The specifications of the chamber are given in Table 2.

Taking readings of experimental variables is important for further data analysis of this research. Depending on the measuring variable, different instruments are needed. The required measuring instruments for this study and their functions are outlined in Table 3.

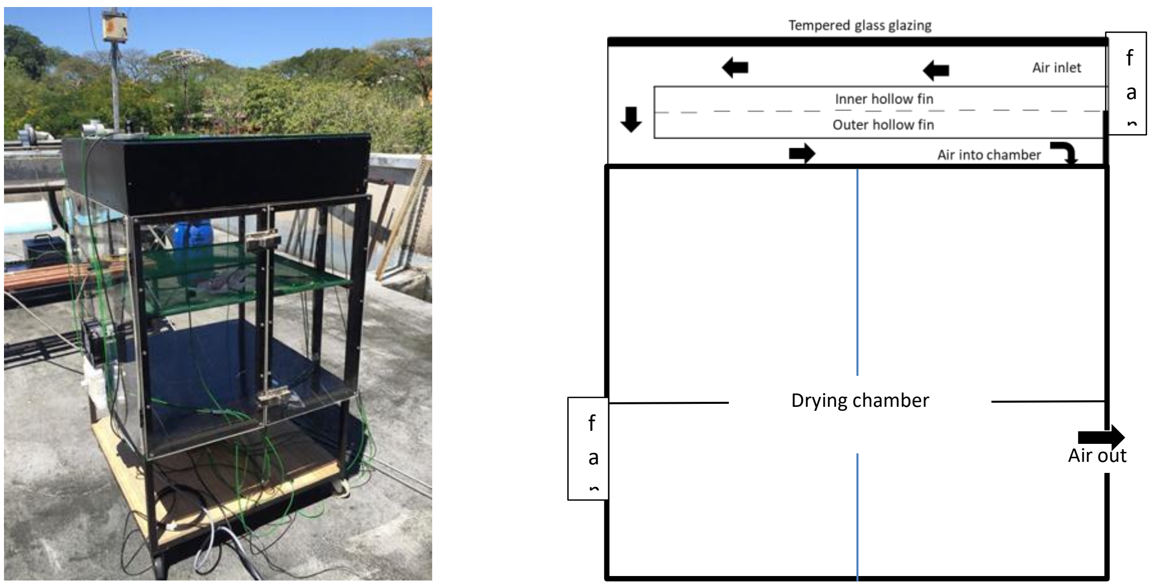

Figure 1. Solar collector mounted to the drying chamber in a greenhouse dryer; (a) photograph, (b) schematic

The four measures are the order of the experimental protocol for studying the greenhouse solar dryer's energy analysis. Instruments and electrical connections were installed prior to the start of the experiment.

(i) From 11AM to 4PM., a greenhouse solar dryer in passive mode with no load is mounted in the open field.

(ii) From the start to the finish of the experiment, data for ambient and device variables is collected every two minutes. Temperature and solar irradiation were recoded as ambient variables. The temperature of the solar collector units, the outlet air from the collector, the outlet air from the chamber, and the inside chamber temperature were all reported as system variables.

(iii) In active mode, the experiment is repeated with a ventilation unit attached to the collector unit. The fans are activated in a similar setup to create faster airflow. The mass flow rate of air in active mode is adjusted and maintained at 0.056 kg/s.

(iv) Drying samples are used to replicate steps 1–3. On the drying tray, 500 grams of *Ficus carica* L. leaves are arranged. The samples were dried in the dryer for 6 hours before being switched off at 4 p.m. The moisture reduction mass is calculated by recording the final weight of the samples.

Table 1. Solar collector unit specifications

Component	Specification
Tempered glass length	65 cm
Tempered glass width	65 cm
Glass thickness	4 mm
Total collector width	65 cm
Total collector length	56.3 cm
Absorber plate material	Aluminum
Number of hollow tubes	12
Size of outer hollow tube	7.6 cm × 4.5 cm
Size of inner hollow tube	5.1 cm × 2.2 cm
Distance between tubes	0.5 cm
Hollow tubes length	55 cm
Insulator material	Insuflex
Insulator thickness	2 cm
Size of air hole	12 cm × 12 cm

2.1. Environmental-Economic Analysis

Although energy analysis is a popular method for reducing thermodynamic efficiencies in dryer systems, thermoeconomics is a different approach for determining the most cost-effective structure and the best thermodynamic efficiency values in each part (Abusoglu & Kanoglu, 2009). Also for complex structures, thermoeconomic is seen as a promising diagnostic method (Kumar, 2017). Solar dryers have been shown to have undeniable gains in carbon footprint reduction compared with the energy-intensive drying process by economic research. According to a review article by Mathew and Venugopal (2018), solar dryers are a cost-effective system that produces high-quality dried goods. For various types of drying goods, the unit cost of useful energy for solar dryers ranged from 0.0034 to 0.015 USD per MJ of energy (Mathew & Venugopal, 2018).

Table 2. Specifications of drying chamber

Component	Specification
Dimension of chamber	55 cm × 65 cm × 65 cm
Material of chamber walls	Acrylic
Wall transmissivity	n.d
Number of doors	2
Tray height	n.d
Material of tray	Stainless steel
Area of air outlet	0.00707 m^2

Table 3. Specifications of drying chamber

Instrument	Function
Thermocouple	Temperature measurement in across 3 different systems i.e. ambient variables, system variables, samples variable. The thermometer used is a K-type using Ni-Cr with temperature range of 0°C-1100°C.
Pyranometer	Solar irradiance measurement on planar surface. This instrument is placed in the open to record ambient solar irradiation during experimentation. Unit measurement in W/m2. The conversion constant of this pyranometer is 5W for one mV recorded.
Anemometer	Airflow measurement to indicate the flowrate of inlet air when dryer in active mode. Unit of measurement in m/s. Airflow measurement is taken at three points at the collector inlet.
Data logger	Automated logging of temperature and solar irradiance readings from the thermocouples. 16-channel logger ADAM (Automated Data Acquisition Module) provided by SERI is used for this experiment.
Weighing scale	To determine the amount of moisture removed during drying process, the samples were weighed using weight scale at regular intervals. Two different scales were used in this experiment; one with 0.01kg sensitivity with 0-30kg range, and one with 0.01g sensitivity with 0-500g range.
Exhaust fan	In active mode, artificial air circulation was initiated. 3 exhaust fans were installed at the inlet of solar collector unit, and one at the bottom of drying chamber to create even flow of air stream. The mass flowrate of inlet air is kept constant at 0.056 kg/s.
Air flow regulator	A regulator unit will be used to regulate fan speed so that desired air flowrate can be achieved.

El-Hage *et al*. (2018) performed an economic analysis to assess how much money can be saved by using commercial solar dryers in Lebanon's environment. The proportion of time the solar dryer is utilised, Pr, the dryer's monthly energy usage, Emonth, and the price of electricity per kWh, PkWh, were used to calculate the monthly energy cost reduction. Depending on the Pr value, which ranges from 0.1 to 1, the monthly energy cost savings for drying 120 kg of various vegetable samples ranges from $130 to $4160 (1).

$$SM = P_r \times E_{month} \times P_{kWh} \quad (1)$$

The solar dryer's capital cost and determined SM were used to calculate the device's simple payback time (PP) (2).

$$PP = \frac{C_{dryer}}{SM} \tag{2}$$

In reality, the percentage of fuel savings varies depending on the form and solar dryer system. Savings range from 20% to 40% in hybrid systems to complete fuel elimination in natural ventilation systems. solar dryer in greenhouse (Liu *et al.*, 2015).

CO2 mitigation is a mechanism for assessing climate change potential and reducing greenhouse gas emissions by limiting overall annual emissions and allowing the market to value any surplus by trading (Nayak *et al.*, 2011). In the carbon credit model, monetary incentives allow transactions between companies and individuals to participate in carbon footprint reduction while also contributing to global fund reduction schemes. The part of energy analysis is carbon credit.

Embodied energy (EE) is the collective amount of energy required to manufacture any goods, products, or services (Prakash *et al.*, 2016). Calculating the amount of energy required to produce a unit of system by accounting for the energy consumed in resource production, resource refining, manufacturing, and transportation is a common variable in environmental analysis (Shrivastava & Kumar, 2017). The energy efficiency measurements serve as a gauge of the total environmental effects of materials and systems since the energy used equates to CO2 output, which causes GHG emissions. The quantification of the materials used in the dryer's manufacture and upkeep during its full life cycle is required for EE estimation. The total EE for the overall equipment was calculated by multiplying the mass values of the various materials by their embodied energy coefficients (EEC), which are normally expressed in MJ kg^{-1} (Hasan & Langrish, 2016).

The time it takes to pay back the EE is known as the energy payback time (EPBT), and it can be calculated as follows (3):

$$EPBT = \frac{Embodied\ Energy}{Annual\ Energy\ Output} \tag{3}$$

Carbon credit is a tool that represents every tradable certificate or permit that gives companies or enterprises the right to emit one tone of carbon or carbon dioxide equivalent, which is vital in the implementation of the pollution trading strategy (Luxmore *et al.*, 2013). . A carbon credit model is widely used to measure the carbon reduction and gained carbon credit associated with the use of solar dryers. The discrepancy between total CO2 mitigation and total CO2 emission is used to measure overall CO2 mitigation over the dryer's lifetime (4).

$$\begin{aligned} Net\ mitigation\ of\ \mathrm{CO2}\ over\ lifetime\ &= Total\ CO2\ mitigation - Total\ CO2\ emission \\ &= [E_a \times n \times X - EE]\ kg \end{aligned} \tag{4}$$

where n is the dryer lifetime, X is the CO2 mitigation per kWh of the dryer and E_a is the annual thermal output energy of the dryer. The equation for X is given as (5):

$$X = \frac{1}{1-L_a} \times \frac{1}{1-L_{td}} \times 0.98 \tag{5}$$

where the first item, La (10%), compensates for lost power consumption, and the second term, Ltd (45%), for lost energy owing to transmission and distribution. As a result, the sum of CO2 mitigation provided by the device, X, is estimated to be 2.01 kg at given La and Ltd values (6).

$$Carbon\ credit = Net\ mitigation\ of\ CO2\ over\ lifetime\ \times D \tag{6}$$

3. Results and Discussion

3.1. Environmental Analysis: Embodied Energy

The total energy required to produce any items – including extraction, processing, manufacture and transportation of the materials that constitutes the product, things or services is called embodied energy. In this section, embodied energy analysis is performed on the greenhouse solar dryer system. The embodied energy of the materials used to build the active mode and dryer under passive modes, respectively, is shown in Table 4.

Table 4. Embodied energy for manufacturing a modified greenhouse dryer

Material	EE coefficient (kWh/kg)	Quantity (kg)	Total (kWh)	Reference
		Ventilation		
Acrylic ducting	10.20	1.31	13.36	(Prakash *et al*, 2016)
Blower Fans	8.89	0.87	7.73	(Shrivastava & Kumar, 2017)
Plastic Dimmer	19.44	0.40	7.78	(Shrivastava & Kumar, 2017)
Nuts and Bolts	8.89	0.05	0.44	(Shrivastava & Kumar, 2017)
		Collector		
Glass cover	7.28	6.25	45.50	(Shrivastava & Kumar, 2017)
Aluminum solar absorber plate	55.28	4.12	227.75	(Shrivastava & Kumar, 2017)
Aluminum sides	55.28	0.98	54.22	(Shrivastava & Kumar, 2017)
Bottom plate	55.28	1.27	70.08	(Shrivastava & Kumar, 2017)
		Drying Chamber		
Acrylic walls	10.20	8.91	90.84	(Prakash *et al*, 2016)
Door bolt	8.89	0.30	2.67	(Shrivastava & Kumar, 2017)
Plastic wire mesh	19.44	0.08	1.56	(Shrivastava & Kumar, 2017)
Bottom plate	55.28	1.27	70.08	(Shrivastava & Kumar, 2017)
Plywood cover	2.88	1.97	5.67	(Shrivastava & Kumar, 2017)
Blower Fans	8.89	0.43	3.82	(Shrivastava & Kumar, 2017)
Plastic Dimmer	19.44	0.40	7.78	(Shrivastava & Kumar, 2017)
Nuts and Bolts	8.89	0.20	1.78	(Shrivastava & Kumar, 2017)
Paint	25.11	1.00	25.11	(Shrivastava & Kumar, 2017)
		Total (kWh)	636.17	

The calculation for embodied energy follows the multiplication of mass of each dryer component to the embodied energy coefficient, which differs for each materials. Combining all three dryer components i.e. ventilation unit, collector unit and drying chamber unit which is equivalent to dryer system in active mode, the embodied energy is determined to be 636.17 kWh. At passive mode, the embodied energy of the dryer is 606.86 kWh, which is 4.8% lower than active mode. As shown in Figure 2, collector unit records the highest embodied energy at 397.55 kWh, which is 62.3% of the total embodied energy. Drying chamber contributes to 32.9% of embodied energy at 209.3 kWh.

Aluminium contributes 422.1 kWh of embodied energy, which is 66% of the total value (Figure 3). This is because aluminium is used in the construction of the double pass-multi hollow solar collector, as well as the frame of the dryer structure. Acrylic sheets contribute to 16% of embodied energy as it is used for the walls of drying chamber, followed by 7% from glass which was used as glazing of solar collector. Paints, plastics, fans and fittings and plywood each contributes to 4%, 3%, 3% and 1% to embodied energy of the system, respectively.

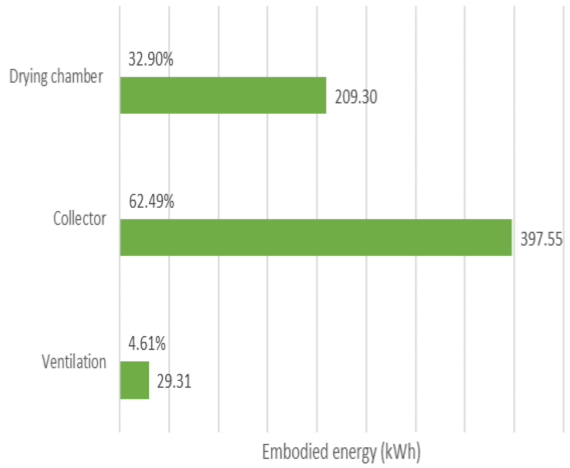

Figure 2. Embodied energy for each solar dryer unit component

3.2. EPBT

Energy payback time (EPBT) is the energy required to compensate the embodied energy used to construct the dryer system. In this analysis, the EPBT is calculated for both active and passive mode. The parameters used in this analysis is shown in Table 5. The sunshine days per year is assumed to be 250 days, with sunshine hour of 6 as the dryer operates from 11AM to 4PM. The fan power used to facilitate air movement, either for air circulation in active mode or air suction in passive mode is taken into consideration to determine the net annual average consumption of electric power by fans. With these parameters, the annual thermal energy output of the dryer is determined to be 61.20 kWh in active mode, and 36.39 kWh in passive mode. Using Equation Y, the EPBT of an active solar dryer is 10.4 years, while passive mode requires additional 6 years at

16.7 years. This values suggest long period for energy to be paid back by the current dryer conditions, where low values in literature suggest a period of 1.14-1.89 years (Prakash *et al*., 2016), (Prakash & Kumar, 2014).

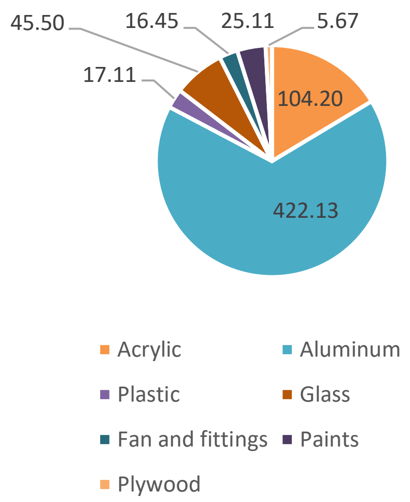

Figure 3. Break-up of embodied energy of different material used for construction of the solar dryer

Table 5. Calculation parameters and assumptions for EPBT

	Active	Passive
Mass of water evaporated	0.37	0.22
Latent heat (kJ/kg)	2381.9	2381.9
Sunshine days	250	250
Fan power (W)	33.6	33.6
# fan	3.00	1.00
Sunshine hour daily	6.00	6.00
Daily thermal output (kWh)	0.24	0.15
Annual thermal energy output (kWh)	61.20	36.39
Energy payback time (years)	10.39	16.68

3.3. Carbon Dioxide Emission, Mitigation and Credit

When energy is generated, so is carbon dioxide. In this environmental analysis, carbon dioxide emission associated with dryer construction is evaluated. The result of carbon emission for active and passive dryer is shown in Table 6. For active dryer, the CO_2 emission per year is 47.14 kg/year, 4.6% more than a passive dryer with CO_2 emission of 44.97 kg/year. This calculation is made using the assumption of 10 years lifetime.

Table 6. CO_2 emission for dryer in active and passive modes

	Active	Passive
Emission average CO_2 per kWh of electricity generation (kg/kWh)	0.741	0.741
Lifetime (years)	10	10
CO_2 emission per year (kg/year)	47.14	44.97

Table 7 shows the calculation for net carbon mitigation and earned carbon credit. This calculation is made using the assumptions of power loss at domestic appliances of 10%, and power loss due to transmission of 45%, and average CO_2 equivalent intensity for electricity generation from coal power plant of 0.98 kg of CO_2 per kWh. Thus, the coefficient of active and passive mode is 2.01 kg (Nayak *et al*., 2011). From these calculations, the total CO_2 mitigation is found to be 1230.15 kg and 731.44 kg for active and passive dryer, respectively for its entire lifetime. Hence, the net mitigation of CO_2 achieved by this dryer system is 593.98 kg, and 124.59 kg respectively. The earned carbon credit is evaluated using the current market price, where 1 kg of CO_2 can be traded from $5 to $20 per tonnes of CO_2. The amount of carbon credit obtained from this dryer system ranges from $0.62 – $2.97 and $12.46 – $59.40, for $1 and $5 basis respectively. This would translate into RM2.58 – RM12.38 and RM51.95 – RM247.66, given current currency exchange of $1 to RM4.17.

Table 7. Net CO_2 mitigation and earned carbon credit of the dryer system

	Active	Passive
X (kg)	2.01	2.01
Total CO_2 mitigation	1230.15	731.44
Total CO_2 emission	636.17	606.86
Net CO_2 mitigation (kg)	593.98	124.59
Earned credit ($)	2.97	0.62
	59.40	12.46

3.4. Economic Analysis

The following economic analysis was performed to determine the energy cost related to dryer operation on monthly basis for active and passive modes. This calculation is to quantify the electrical energy load utilizes by the system, hence the cost needed to pay for its electrical consumption. By taking into account the power rating of fans, the total device put in use, and the daily operation hour i.e. sunshine hour, daily power input can be determined in kWh/day. Assuming 20 days of monthly working day and current electricity price of RM 0.3945 per kWh, the monthly energy cost for dryer operation is RM 4.77 and RM 1.59 for active and passive dryer, respectively. The summary of this analysis is given in Table 8.

Table 8. Energy costing for solar dryer operation on monthly basis

	Active	Passive
Power (W) per device	0.0336	0.0336
# device	3.00	1.00
Sunshine hour daily	6.00	6.00
Monthly working days	20.00	20.00
Electricity price (RM/kWh)	0.3945	0.3945
Power input, Eday (kWh/day)	0.6048	0.2016
Power input, Emonth (kWh/month)	12.096	4.032
Energy cost (RM/month)	4.77	1.59

4. Conclusions

The fan power needed to facilitate air movement, whether for active air circulation or passive air suction, is considered when calculating the net yearly average consumption of electric power by fans. The dryer's yearly thermal energy production is calculated to be 61.20 kWh in active mode and 36.39 kWh in passive mode. Environmental analysis includes the quantification of embodied energy, energy payback time (EPBT) period, as well as CO2 emissions per year, carbon mitigation and carbon credit. The embodied energy of a passive dryer is 606.86 kWh and EPBT of 16.68 years, while for active dryer the values are determined at 636.17 kWh and 10.39 years, respectively. CO2 emission for passive dryer is 47.17 kg per year, net CO2 mitigation of 124.6 kg, and earned carbon credit of RM 2.58 – RM 12.38. Active dryer has CO2 emission of 47.14 kg, net CO2 mitigation of 594 kg, and earned carbon credit of RM 51.95 – RM 247.66. Economic analysis on this dryer reveals the energy costing associated to its operation, where RM 4.77 and RM 1.59, are needed on monthly basis.

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