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Solar Drying System for Drying Empty Fruit Bunches

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Abstract: *In this paper, the drying characteristic of Empty Fruit Bunches (EFB) of oil palm is presented. The EFB, a waste of oil palm processing was used as the test sample and dried using a solar drying system that was built. The system used was comprised of six double-pass solar collectors with porous media in the second channel, which were connected in a series of three collectors in two banks and a drying chamber. Two conditions of the EFB sample were considered in the drying test; treated and untreated. A simple water washing treatment was used to treat the first sample to reduce its ash content whereas the second sample was untreated in its original condition. The EFB samples were dried until equilibrium moisture content below 10 mf wt% was reached, a condition required to achieve a number of purposes in energy applications and storage of biomass material. From the results obtained, it was found that the samples were successfully dried from an initial moisture content of 170.68 mf wt% to final moisture content of 3.85 mf wt% for the untreated sample and from 376.14 mf wt% to 4.36 mf wt% for the treated sample in 66 hours of solar drying.*

Keywords: Solar drying, EFB, moisture content, ash content

1. INTRODUCTION

Malaysia is the largest producer of palm oil in the world and has around 4.3 million hectares of oil palm plantation. The country also produces an average of 81.5 million tonnes of fresh fruit bunches. Among other contributors, palm oil industry represents the highest contributor of solid wastes and generates more residues during harvesting, replanting and milling processes. The residues that come from the milling processes are fruit fibres, shells and empty fruit bunches (EFB) which have good potential as energy resources. Other residues which include trunks and fronds are also abundant at the plantation area.[1] These wastes are currently left on the ground or burned due to the inconvenience of handling and transporting the wastes to a proper site which are causing many environmental problems. For example, open burning is not only causing air pollution and green house effects but also creates other health issues.

Biomass is an organic matter that can be converted into useful energy. There are many processes available for converting biomass waste into valuable fuels such as fuel oil, fuel gas or higher value products for chemical and biotechnology industry. The waste can be converted into useful energy by direct combustion, pyrolysis, liquefaction or gasification.[2–4] However, before the waste can be used effectively in these processes, some pre-treatment processes should be applied to the sample such as size reduction, drying treatment and washing treatment.

Biomass products are dried to achieve standard value of moisture content to avoid damage from infestation of microorganisms and other pests, and also to increase the yield of the products. However, if the products are over dried, it will cause a decrease in its value.[5] Biomass with moisture content of less than 10 mf wt% is required to avoid microorganism attack which affects the end-product quality and to achieve a number of purposes in energy applications and storage of biomass material. At this rate, the enzymes inside the products become inactive.[6,7]

Solar drying system has three types of drying modes: direct, indirect and mixed-mode. In the direct mode dryer, the product is directly exposed to solar radiation. This type of dryer mainly consists of a drying chamber that has a transparent glass or plastic cover. Biomass product is placed on a perforated tray to be heated rather directly.[8] In the indirect mode, the product is not directly exposed to direct solar radiation. The dryer basically consists of a solar collector and a drying chamber. Biomass product is placed in an opaque drying chamber, which is heated by the air from the collector connected to it. However, the performance of the indirect mode dryer depends on the efficiency of the collector. This type of dryer is more efficient than the direct mode dryer or open sun drying and was reported that it could produce higher operating temperature.[9] As for the mixed-mode solar dryer, the performance is found to be most effective and particularly promising in tropical humid areas where climatic conditions favour direct sun drying for agricultural products. This type of dryer basically consists of a cabinet-type solar dryer with a transparent top cover and connected to a solar collector. Normally, natural convection works the best for the mixed-mode dryer since it utilises heat from direct solar radiation as well as the convective energy of the heated air from the collector.

The purpose of this study was to dry EFB, a waste from palm oil industry in a solar drying system that was designed until moisture content of below 10 mf wt% is reached. The solar drying system which comprised of six double-pass solar collectors with porous media in the second pass were built and connected in a series of three collectors in two banks and a drying chamber. A simulation study on a double pass solar collector with porous media reported that in order to produce the highest outlet temperature and efficiency, the height of the upper pass must be at 1.00 cm and for the second pass at 10.00 cm. This was based on the effective length of the collector which was between 240 cm to 280 cm, while the effective width of the collector was between 100 cm to 140 cm.[10] Therefore, in this study, the collectors constructed were based on this suggestion.

1.1 Review of a Solar Drying System

Ramana Murthy[11] reviewed several types of solar driers developed in several countries of Asia-Pacific region, and he found that the highest potential for drying and the popular ones are the natural convection cabinet type, the forced convection indirect type and the green house type. These types of dryer are a combination of the direct and indirect modes. Ekechukwu and Norton[9] also reviewed on the classification of solar energy dryers. They found that there are two generic groups of solar energy dryers, which can be identified as passive or natural circulation solar energy dryers and active or forced convection solar energy dryers. In addition, there are three sub-groups of these dryers that can be identified as the integral type (direct mode), distributed type (indirect mode) and mixed-mode type.

The performance of the solar drying system is highly influenced by the performance of the collector. Therefore, several researches have been conducted in order to improve the performance of the solar collector and to produce better quality end product. As an example, Bolaji and Olalusi[12] studied the design, construction and performance of a mixed-mode solar dryer for food preservation. In the construction of the solar dryer, they designed the drying cabinet that was able to absorb solar radiation directly through the transparent walls and roof. At the same time, heated air from a separate solar collector is passed through a grain bed. They found that the temperatures inside the dryer and solar collector were much higher than the ambient temperatures during day time. Tarigan and Tekasakul[13] did a research study on a mixed mode natural convection of solar dryer integrated with a simple biomass burner and bricks for storing heat. The dryer was used to dry 60–65 kg of unshelled freshly harvested groundnuts. The drying efficiency of the solar component alone and the efficiency of the burner with heat storage in producing useful heat were 23% and 40%, respectively. Forson et al.[14] had designed a prototype of the mixed-mode natural convection solar crop dryer for drying cassava and other crops. They found that a minimum of 42.4 m^2 of solar collection area was required to obtain the drying efficiency of 12.5%.

Sopian et al.[15] designed and fabricated a solar assisted drying system which consisted of a solar collector array, auxiliary heater, drying chamber and air distribution system. The solar collector was a double-pass type with an upper and lower channel. The lower channel of the solar collector was filled with porous media that increased the outlet temperature and improved the performance of the system as the porous media acted as heat storage. They found that the drying system was capable of drying oil palm fronds from moisture content of about 63 mf wt% to moisture content of about 15 mf wt% with drying time of about 7 h. The overall system efficiency was about 25%. Naphon[16] studied numerically the heat transfer characteristics and performance of the double-pass flat plate solar air heater with and without porous media. They found that the solar air heater with porous media gives 25.9% higher thermal efficiency than that without porous media.

The heat transfer characteristics and thermal performance of five different characteristics of solar air heaters were studied numerically by Naphon and Kongtragool.[17] They found that the conventional solar air heater with a single glass cover produced the lowest thermal efficiency because the forced convective and radiative heat losses were dominant. They also found that the position of the absorber plate was an important factor to increase the thermal performance of the solar air heater. Liu et al.[18] did a parametric study on the thermal performance of a solar air collector with a v-groove absorber with the objective to enhance the heat transfer rate between the air and the absorber by increasing the heat transfer surface area. They found that the v-groove collector has considerably superior thermal performance to the flat-plate collector.

A solar dryer for drying pineapple which comprised of a drying chamber, a biomass stove and a solar collector was developed by Elepaño and Satairapan.[19] The drying chamber was a cabinet type with a capacity of 50 kg of sliced pineapple per batch for drying. The biomass-stove was fueled by coconut shell or wood charcoal. The solar collector of size 90 cm × 120 cm was attached at the backside of the drying chamber and tilted at 15° from the horizontal. They found that, about 50 kg of pineapple with an initial moisture content of 85% can be dried to a final moisture content of 20% based on wet basis for about 18 hours at average temperature of 60°C while consuming 2.0 kg per hour of coconut shell/wood charcoal.

El-Beltagy et. al[20] studied the indirect forced convection solar drying system for strawberries, which consisted of a solar collector with a W-corrugated black aluminum sheet absorber and a drying chamber. A fan was used to force the air in the solar collector. The heated air was directed to the drying chamber through the bottom side of the dryer. The drying system can be tracked continuously to face the sun on movable wheel. A single layer of pretreated strawberries was placed on the trays inside the dryer that took about 10 h to dry. They found that the temperature of 47°C was adequate for drying strawberries, as this drying system was successful in drying the strawberries from initial moisture content of 88.3% to final moisture content of 40% on wet basis. Mohanraj and Chandrasekar[21] had designed and fabricated a forced convection solar dryer for drying copra. This system comprised of a flat plate solar air heater with dimension of 2 m × 1 m that was connected to a drying chamber. One side of the collector was fixed with a fan to force the air in the collector. They found that the copra's initial moisture content of about 51.8 mf wt% was successfully reduced to 7.8 mf wt% and 9.7 mf wt% in 82 h for trays at the bottom and top layer of the drying chamber, respectively.

Banout et al.[22] studied the comparison between the performance of a new designed double-pass solar dryer (DPSD) with a typical cabinet dryer (CD) and a traditional open-air sun drying to dry red chilli in central Vietnam. They found that the samples were successfully dried to moisture content of 10% on wet basis in 32 h using the DPSD and 73 h using the CD. However, the drying time of open-air sun drying took more than 93 h. The overall drying efficiencies of the DPSD and CD were 24.04% and 11.52%, respectively while the overall drying efficiency of open-air sun drying to reach the final moisture content of 15% on wet basis was at 8.03%.

1.2 Heat Transfer Mechanism

The principle involved in collecting the solar energy is rather simple depending strongly on the receiving surfaces, which are able to absorb as much as possible of the incoming solar flux. Heat losses poised the main problem, which does not just rely on the absorbing surface. It is evident that heat transfer processes are therefore essential and play a major role in the design of a flat plate collector.

The actual useful energy gain of the flat-plate solar collector is as follows; with the assumption that the losses based on the inlet fluid temperature is negligible:[23]

$$Q_U = A_C F_R [S - U_L (T_i - T_a)] \tag{1}$$

where S is the absorbed solar radiation, U_L is the overall heat loss coefficient, A_C is the effective collector area that is exposed to the incoming solar flux, T_i is the inlet temperature of the working fluid, T_a is the ambient temperature and F_R is the heat removal factor. The absorbed solar radiation, S is obtained from the meteorological data and the heat removal factor is calculated as follows:[24]

$$F_R = \frac{J_{CP}}{A_C U_L}\left[1 - e^{-(A_C U_L F_P / J_{CP})}\right] \tag{2}$$

where J is the mass flow rate, c_P is the constant pressure specific heat capacity, and F_P is the plate efficiency factor.

Solar collector efficiency is calculated by taking the ratio of the total solar energy absorbed to the total solar energy received by the collector. When the heat losses of the collector increase, the efficiency of the collector will reduce. The major heat losses in a collector are from the upper side (top cover). It is due to the top face of the collector, which cannot be insulated. As a result, the thermal losses in a collector increases when the temperature of the absorber plate and glass cover increases. However, the sides and back of the collector can be insulated adequately.[25] The total heat loss of a solar collector is defined as follows:

$$U_L = U_T + U_S + U_B \tag{3}$$

where U_T, U_S and U_B is the heat losses from top cover, sides and bottom of a collector.

The upper loss U_T is the total sum of energy lost from the top surface of the solar collector to the surroundings by convection and radiation process. The heat loss through the upper side of the collector is caused by the difference in temperature between the glass cover and the ambient temperature. The basic equation for U_T is proposed by Hottel and Woertz[26] as in equation below:

$$U_T = \left[\frac{N}{\frac{C}{T_p}\left[\frac{T_p - T_a}{N+f}\right]^e} + \frac{1}{h_w} \right]^{-1} + \frac{\sigma\left(T_p^{\,2} + T_a^{\,2}\right)\left(T_p + T_a\right)}{\frac{1}{d} + \left(\frac{2N + f - 1}{\varepsilon_g}\right) + g - N} \tag{4}$$

C, d, e, f and *g* are the function or constants of equation (3.4) and given by Malhotra et al[27] as follows:

$$C = 204.429\,(\cos\beta)^{0.252} / L^{0.24}$$
$$d = \varepsilon_p + 0.0425N\left(1 - \varepsilon_p\right)$$
$$e = 0.252$$
$$g = 0.0$$
$$f = \left(\frac{9}{h_w} - \frac{30}{h_w^{\,2}}\right)\left(\frac{T_a}{316.9}\right)\left(1 + 0.091N\right)$$

A study done by Garg et al.[28] showed that in order to find the value of U_T, the proposed equations of Malhotra et al. is suitable to be used because it gives the best agreement with iterated values. The sides and bottom loss of the collector can be calculated by the following equations by Sukhatme.[29]

Side:

$$U_S = \frac{(P_C + L_C)t_C\lambda}{A\varpi} \tag{5}$$

Bottom:

$$U_B = \frac{\lambda}{\varpi} \tag{6}$$

The efficiency of the collector is calculated as follows:[30]

$$\eta_c = \frac{h(T_o - T_i)}{IA} \tag{7}$$

where Nu is the Nusselt number, Ra_L is the Rayleigh number, L is the effective length and β is the thermal expansivity and calculated as follows:

$$Nu = \frac{hL}{k} = 0.069 Ra_L^{1/3} \Pr^{0.074} \tag{8}$$

$$Ra_L = \frac{g\beta'(T_s - T_a)L^3}{\alpha\nu} \tag{9}$$

$$L = \frac{A_s}{P} \text{ and } \beta = \frac{1}{T} \tag{10}$$

2. EXPERIMENTAL

A solar drying system has been designed and constructed in Universiti Sains Malaysia USM), in the northern region of Peninsular Malaysia. The system consisted of a drying chamber and six solar collectors of double-pass type with porous media in the second pass of the collector.

The length of each collector was 240 cm and the width was 120 cm. The collector was designed according to the measurements suggested by Ooi[10] in his research work. He found that the bigger the surface area, the higher the heat transfer rate to useful energy is. However, collectors with small surface area gave a higher efficiency but lower output temperature. Therefore, an optimisation of parameters was found to obtain the best output. In order to produce the highest outlet temperature, an absorber plate made of aluminium sheet was placed between the upper and bottom channel of each collector with height at $H_1 = 1.0$ cm at the top pass and $H_2 = 10.0$ cm at the bottom pass as shown in Figure 1. The plate was painted matt black to increase the absorber's absorption capacity. The collector's frame was made of plywood, which was also painted black and a single sheet of glass was used as top cover. The bottom and sides of the collector were insulated with polystyrene to minimise heat losses. Solar radiation through the transparent glass cover of the collector was absorbed by the absorber that heated the air inside the first pass of the collector, before flowing to the second pass. The porous media acted as a good thermal storage and assisted in maintaining high temperatures in the later part of the afternoon.

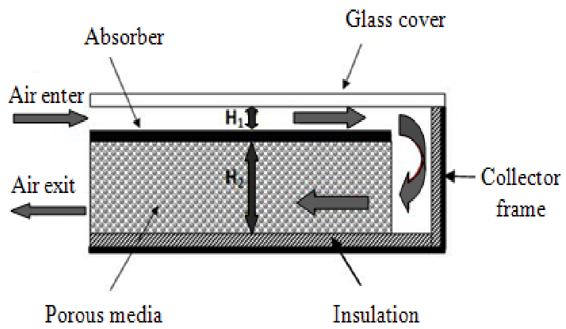

Figure 1: The side view of the solar collector.

The dimensions of the drying chamber were 120 cm × 120 cm × 240 cm as shown in Figure 2. The external walls were made of plywood which was painted black while the internal walls were made of zinc and insulated with polystyrene of thickness 5 cm. The heat absorbed by the interior walls was greatly influenced by direct solar radiation through the top glass cover on the roof besides the heated air from the collectors. There were three different levels of wire mesh trays inside the chamber where the samples were dried. A small exhaust outlet on the upper side of the drying chamber was made to facilitate air movement out of the chamber.

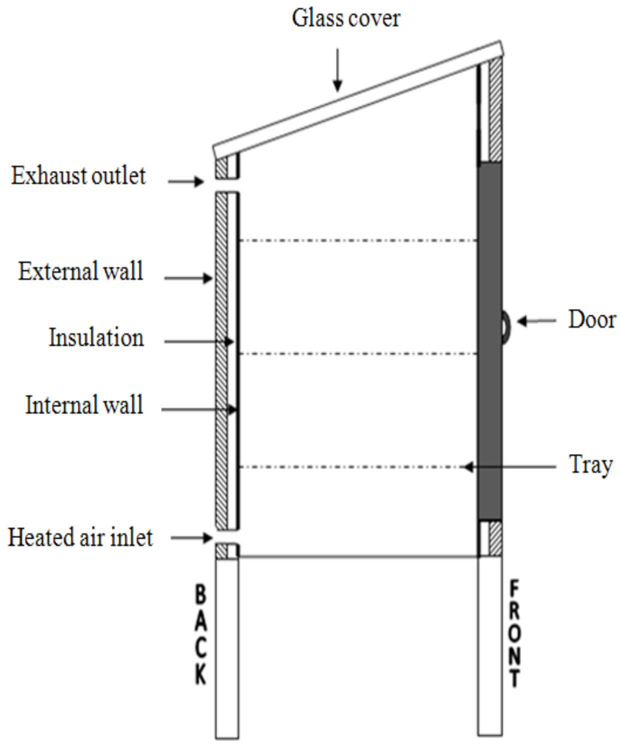

Figure 2: The side view of the drying chamber.

The layout of the solar drying system is as shown in Figure 3. There were two sets of three collectors connected in series with air entrance inlet in the upper channel of the first collector for each set. The heated air from the two banks of solar collectors was finally directed to the drying chamber by connected insulated hoses. The solar collection area in this work was 17.3 m^2 which was about two and a half times smaller than a similar system in another research study as in Forson et. al[14] but utilising porous media as heat storage.

For the drying experiment, EFB were taken fresh from a local oil palm industry in whole bunches which had gone through the sterilisation process and were very wet. Two conditions of the EFB samples were considered in this study, which were treated and untreated samples. All samples were cut into smaller size ranging around 2–3 cm and divided into two. The first EFB sample was treated using a simple water washing treatment to reduce the ash content by soaking in tap water for about 20–30 min. For every 100 g of sample, 5 l of tap water at room temperature was used.[31] After undergoing the water washing treatment, the sample was drained for 30 min. On the other hand, no treatment was applied to the other EFB sample.

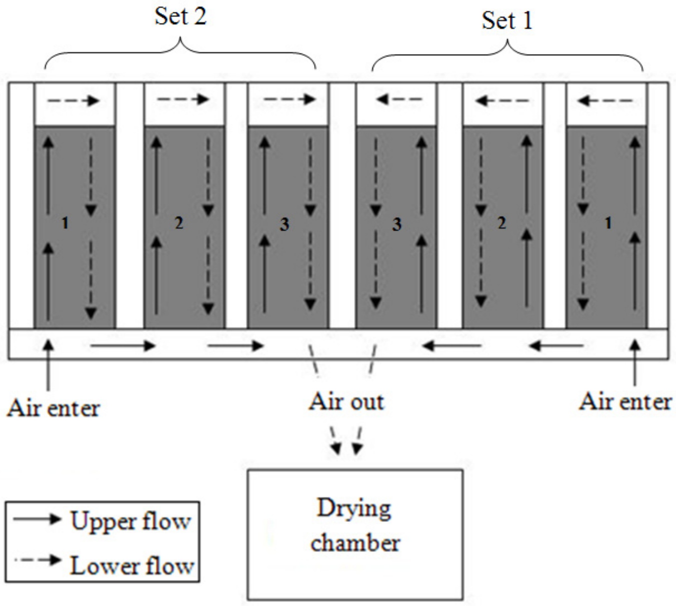

Figure 3: The configuration of the solar drying system.

Since there are three tray levels in the drying chamber, a total of 8–10 kg of biomass can be dried at once. However in this work, only one level tray was used where both the treated and untreated EFB of around 2.5 kg in total were placed on the middle tray level inside the drying chamber next to each other. The weight of the samples before and after the drying process on each day was measured and the moisture and ash contents were also determined. The samples were dried until equilibrium moisture content of below than 10 mf wt% was reached. As a part of this study, the hourly solar irradiance were measured using a Kipp and Zonnen Pyranometer and a Meteon Datalogger. Data were taken every second started from 9.30 AM to 5.00 PM during the period of drying. The weather condition of each drying period were also observed.

The equilibrium moisture content was assumed reached when the weights of the samples did not change significantly during the drying period. During the drying process, water was gradually removed from the biomass sample until it reached equilibrium weight where most of the water has been evaporated. The moisture content of the samples on each drying day was determined by ASTM E871 Method.[32] The samples were placed inside the oven for about 24 h at 105°C. The moisture content of a sample is defined as the weight of water in the sample as a percentage of its dry weight determined by the following equation:[33,34]

$$MC = \frac{W_m - W_d}{W_d} \times 100\% \tag{11}$$

After the required moisture content was reached, the ash content of the samples (both washed and unwashed) was determined. The ashing test was conducted to study the effect of water washing pre-treatment on the percentage of the ash content of the samples. The measurement of the ash content of the samples was determined using the National Renewable Energy Laboratory (NREL) Standard Analytical Method LAP005.[35] The sample was placed in a muffle furnace for about 6 h at 575ºC. After 6 h, the samples was removed and cooled in a desiccator for one hour before the weight was taken. The ashing test is normally carried out directly after the moisture content measurement was done as biomass sample such as EFB is hygroscopic in nature. The ash content of the sample can be calculated by the following equation:[35]

$$AC = \frac{W_{SFD}}{W_{SOD}} \times 100\% \tag{12}$$

3. RESULTS AND DISCUSSION

3.1 Drying Experiment of a Mixed-mode Solar Dryer

The drying experiment to investigate the weight loss and moisture content of the EFB samples was carried out for 9 days continuously (66 h) at which the average solar radiation ranged between 293–733 W m^{-2}. The lowest solar irradiance throughout the whole nine days of drying process was at 22 W m^{-2}, which was recorded on day 8 during raining at 9:35 AM. The highest maximum solar irradiance of 1181 W m^{-2} was recorded at 12:49 PM on day 9, which was considered as a sunny day. In a solar drying system, the intensity of the solar radiation received on each drying day will affect the efficiency of the system. More radiation received means more heat will be obtained in the solar drying system.[36] It was recorded that the average temperature of the drying chamber for the period of drying varied between 36–45ºC at ambient temperature of 23–28°C. Most of the days were cloudy with some sunny mornings, which are the typical weather in Malaysia.[37] It was noted that it had rained on the eighth day.

The temperature of the drying chamber plays an important role in the drying efficiency. When the drying chamber's temperature becomes higher, it will speed up the drying process, hence making the drying time shorter. In this experiment, the heated air was supplied from the solar collectors to the drying chamber through the insulated hoses and from the top glass cover on the roof of the drying chamber. However, it was observed that the average temperature of the drying chamber was much lower compared to the temperature of the solar collector. The heat losses due to ineffective insulation and the exhaust outlet in the drying chamber were probable causes. In addition, the high moisture content of the samples also affected the temperature of the drying chamber causing the heated air to become moist and reduced the temperature rather significantly.

Figure 4 shows the weight of the treated and untreated EFB samples for each drying day. The weight of the samples before and after drying was measured for each drying day. The treated sample as described in Section 3 was placed in the drying chamber at the same level with the untreated sample for drying at all times. The weight of the samples for both treated and untreated was initially 1552.31 g and 1000.04 g, respectively.

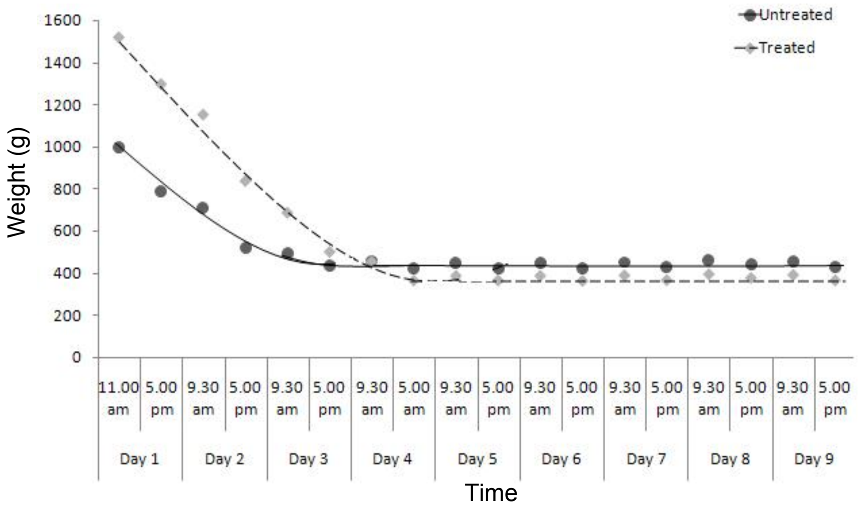

Figure 4: Weight of samples for each drying day.

From the results obtained, it can be seen that the weight for both treated and untreated samples decreased drastically in the first three days even though the average solar radiation intensity at that time was between 450–570 W m^{-2}. However, it is clearly seen that the weight of both samples became stable after three days for the untreated sample and four days for the treated sample. This happened when the surface of the samples reached the hygroscopic threshold and entered the deceleration zone where the evaporation inside the sample began. At this time, water (in liquid form) did not exist anymore but instead appeared in vapour form.[38] In the next five or six days of drying, the weight of both samples showed very little change or no change at all which means that the equilibrium weight for both samples was achieved even though the average solar radiation intensity was higher than the first three days except when it was raining. It was also observed that in the morning before the start of the drying process for that day, the weight of both samples was slightly higher than the previous day. This happened due to its hygroscopic nature, which is capable of absorbing moisture from a humid environment and losing moisture in a dry environment.[31] At the end of the experiment, the untreated sample was found to be heavier than the treated sample even though the treated sample was much heavier initially. This is due to the washing treatment that was applied which has removed some of the dirt, ash and oil off the sample.

At the beginning of the experiment, the initial moisture contents for both treated and untreated samples were 376.14 mf wt% and 170.68 mf wt% (equivalent to 79.00% and 63.06% in wet basis), respectively. Referring to Figure 5, after nine days of drying, the moisture content of the treated sample reached 4.36 mf wt% (equivalent to 4.18% wet basis) while the untreated sample 3.85 mf wt% (equivalent to 3.71% wet basis). Moisture content of below 10 mf wt% was reached in only two days (13.5 drying hours) for the untreated sample and three days (21 drying hours) for the treated sample. After three days of drying, the moisture content for both samples did not change much as they have reached the equilibrium state and that most of the moisture have been evaporated.

It was found that the ash content of the untreated sample was at 4.98 mf wt% which is higher than the treated sample which was at 2.86 mf wt%. This result indicated that the treated sample which achieved ash content of below 3 mf wt% had met the condition required for the purpose of other energy applications such as fast pyrolysis process to derive high quality bio-oil.[39]

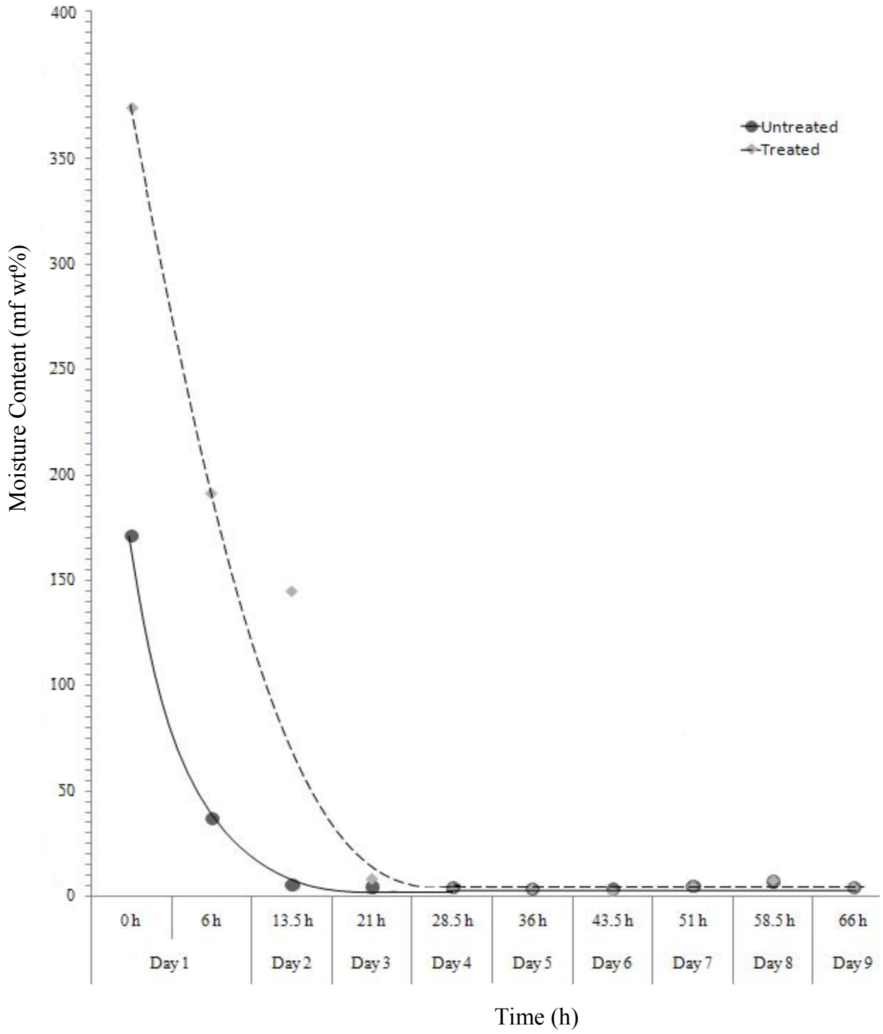

Figure 5: Moisture content of sample for each drying day.

3.2 Thermal Efficiency of a Mixed-mode Solar Dryer

In a mixed-mode type solar dryer, the direct solar radiation through the top transparent cover of the drying chamber plays an important role together with the heated air from the solar collectors in the drying of the EFB samples. For the solar collector, the average temperature obtained for the nine days of drying period were between 52.79–73.68°C. The average temperature for the absorber plate was between 61.38–87.76ºC whereas the average temperature of the drying chamber was between 35.86–45.22°C. The decrease in temperature in the drying chamber was mostly due to the exhaust outlet on the top part of the chamber.

Besides, the high moisture content of the EFB samples had affected the temperature of the drying chamber as well resulting in the heated air becoming moist while lowering the temperature of the drying chamber. In addition, the average solar radiation during the nine days was around 524.1 W m^{-2} and the average upper loss U_T of the solar collector was found to be around 4.32 W m^{-2} K^{-1} which was rather high causing the useful gain of heat only around 60%. However, the back and side losses are much smaller which was around 28% of the total loss due to ineffective insulation.

Since the drying system was operating in natural convection, the efficiency of the collector was found to be rather low of around 2–6%. The surface area of the solar collector dominated by the number of collectors used has not much effect on the efficiency of the drying system as the system was operating in natural convection and hence, a low efficiency is expected.

In this study the drying efficiency is discussed in terms of the drying rate percentage. The percentage of the drying rate is calculated from the following equation:[12]

$$\frac{dM}{dt} = \frac{\left(M_i - M_f\right)}{t} \times 100 \tag{13}$$

The results obtained for both treated and untreated samples are presented in Figure 6. It is seen that the percentage of the drying rate was decreasing with increasing drying time. During the first 30 h, it was observed that the drying rate decreased very quickly. After 30 h of drying, the drying rate decreased very slowly because most of the water in the samples has been evaporated. When the moisture content of the surface reached equilibrium, the drying rate further decreased towards zero.

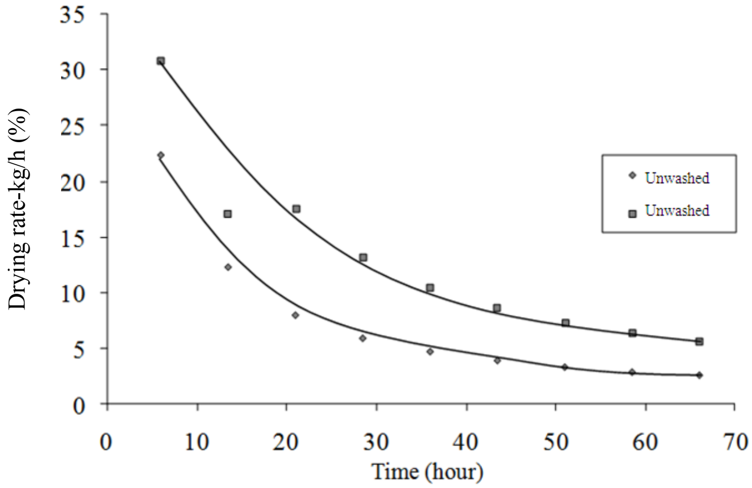

Figure 6: Drying rate of washed and unwashed samples.

4. CONCLUSION

From the results obtained, it can be concluded that the double-pass solar drying system with porous media designed and used in this work has great potential in drying EFB in a rather short time than most work elsewhere. It has been successful in drying EFB from a very high moisture content exceeding 170 mf wt% to below 10 mf wt% in 13.5 h for the untreated sample and 21 h for the treated sample. The solar collection area is smaller by two and a half times compared to another work utilising similar mode system, hence making it more economically viable.

5. ACKNOWLEDGEMENT

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