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Performance of a Solar Greenhouse Dryer for Water Hyacinth

Phatchareephon Niroka*, Gunn Panprayun*,[1], and Piangjai Peerakiatkhajohn*

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ABSTRACT

The development of new methods to utilize solar energy is critical to lower greenhouse gas emissions and provide sustainable livelihoods for small business owners in rural areas. Solar greenhouse dryers are simple and low-cost structures that can be modified for a variety of applications. This study evaluated the performance of a solar greenhouse dryer for drying water hyacinth. The solar dryer was established in Nakhon Pathom, Thailand and consisted of a parabolic roof structure covered with polycarbonate sheets. A ventilation system was designed using fans controlled by relative humidity sensors and powered by a solar panel. The drying system had an overall efficiency of 63% for 100 kg of fresh water hyacinth with a highest temperature of 59°C. In comparison with natural sun drying, the solar dryer produced more product in a shorter amount of time. In addition to regulating the climatic conditions, this solar greenhouse prevented insect infestation, and improved the product quality. The payback period was estimated to be about 1.5 months. This study can be used as a guideline to produce dried water hyacinth for cushioning material, or other products. Also, this solar dryer offers a promising solution for effective drying of other agricultural or food products.

1. INTRODUCTION

Laboratory animals, especially rodents such as guinea pigs and mice, play a major role in research and education in science and medicine worldwide. Thailand established the National Laboratory Animal Center (NLAC) in 1971 at Mahidol University, Salaya, Nakhon Pathom to regulate the quality and quantity of laboratory animals in Thailand. In the breeding process, a large amount of bedding material is required to comply with international standards. Sawdust is currently the main bedding material, which is imported from the United States of America (USA). So, the NLAC has looked for an alternative material for bedding, which is environmentally friendly and can be produced in collaboration with the local community. A potential source of biodegradable material suitable for bedding production is water hyacinth, an aquatic weed that is considered a nuisance in many countries. According to an NLAC study, dried water hyacinth stems are suitable for animal bedding production because it has a high fiber content and soft structure, can absorb a large amount of water, does not disintegrate, and provides a dust-free environment. This led to the establishment of the Community Enterprise Nara Pirom Group Network, Nakhon Pathom, Thailand to produce dried water hyacinth for use as animal bedding.

In general, natural sun drying is an easy and cheap process to create dried products with an extended shelf life. Nakhon Pathom province receives an average daily solar exposure of approximately 18.5 MJ/m^2-day, higher than the national average solar radiation of 17.6 MJ/m^2-day. So, it is likely that there is sufficient solar radiation to use as an energy source [1].

For this reason, the Nara Pirom group has considered the natural sun drying method for the water hyacinth drying process. Unfortunately, the traditional method is considered as an open system that is affected by variable weather conditions and contamination by insects and dust. In addition, the appearance and quality of the dried product is inconsistent. Consequently, the dried products from this method rarely meet international quality standards [2]-[6]. To solve these problems, modifications to solar drying technologies are being evaluated for a wide variety of agricultural and food products. In one recent study, products were dried in a closed system solar dryer which raised the drying temperature. The main advantages of a closed system include protection from pests, flies, rain, and dust [4].

A solar greenhouse dryer designed with a parabolic dome is one of the popular types of solar dryer because it is easy to build, can have a large drying capacity, and relatively efficient thermal performance [7]. Moreover, this technology is easy to use and suitable for small scale production, creating a way to generate income for a community. Most researchers classify solar dryers into two types based on their operation mode, namely natural convection and forced convection. Natural convection solar

*Faculty of Environment and Resource Studies, Mahidol University, 999 Phuttamonthon Sai 4 Road, Salaya, Nakhon Pathom 73170, Thailand.

[1]Corresponding author:
Tel: +66 2441 5000 ext. 2215.
Email: gunn.pan@mahidol.edu

dryers work on the thermosyphon effect. Air is heated and circulated by thermal updraft and needs no external source of energy required. On the other hand, forced convection solar dryers contain an exhaust fan to increase airflow rate. The forced convection dryer has a greater drying rate compared to rates obtained by natural convection solar dryers. Forced convection dryers are better suited for high moisture content crops [5], [8]-[15]. This research tested a forced air convection solar greenhouse dryer. The general principle of solar greenhouse drying is based on the greenhouse effect. Short wavelength solar radiation passing through a transparent roof heats both products and materials inside the solar dryer. The warmed objects emit long wavelength solar radiation, which cannot pass through the transparent cover, resulting in increasing the inside temperature. As the product moisture evaporates, it is removed through an outlet vent in the top of the solar dryer. The moist air is replaced by dry air drawn in through an inlet [5], [16], [17].

Several studies have reported on the performance of parabolic greenhouse solar dryers for food and agricultural products. For example, Janjai and co-workers developed a ventilated solar dryer for drying chili [7]. The parabolic shaped dryer promoted higher temperatures and shorter drying times than traditional sun drying, and the drying efficiency increased with larger loads. Moreover, the product obtained by this dryer had good quality color and texture. The performance of a village-scale solar greenhouse dryer for drying longan and banana has been reported [16]. The solar dryer showed advantages in its performance by requiring shorter drying times and providing higher quality product than the natural sun drying method. A large solar greenhouse dryer for drying chili and banana achieved better color quality and shorter drying time compared with traditional sun drying [18]. The performance of a large-scale solar greenhouse dryer was tested during drying of chili, banana, and coffee in Laos. The study found that using the solar dryer provided shorter drying times than natural sun drying for all products tested. The products obtained in this solar dryer had good quality [19]. A greenhouse solar dryer combined with a LPG gas burner was developed to produce osmotically dehydrated tomatoes. This method solved problems caused by rain and cloudy periods, allowing continuous drying of product [20]. In another study, a large-scale solar greenhouse dryer for drying chili demonstrated reductions in drying time and better quality of color compared to natural sun dried products [17]. The artificial neural network (ANN) model of a parabolic greenhouse solar dryer for drying lychee were studied. In comparison with traditional sun drying, the solar dryer used less drying time and provided good quality dried product. The results were in good agreement with the ANN model [21]. The performance of a parabolic greenhouse solar dryer for drying cayenne pepper was examined. The study found that drying the cut pods in the solar dryer significantly reduced the drying time. There was no significant difference of the capsaicin content between each experiment [22]. To improve the performance of the solar drying system, a parabolic hybrid dryer combined with a rice husk burning system for drying banana was built. The rice husk burner had high efficiency. The hybrid solar dryer showed considerable improvement in drying time when compared to traditional sun drying, and the problem of drying during cloudy and rainy days was solved [23]. A large-scale solar greenhouse dryer combined with phase change material (PCM) was examined for drying chili. This solar dryer with PCM thermal storage achieved higher efficiency and shorter drying times than without the PCM. PCM thermal storage can be used for drying during fluctuating weather conditions [24]. Recently, a detachable solar greenhouse dryer for drying potato produced dried product with better visual appearance than that of natural sun drying and was free from any contaminants. In contrast, the natural sun-dried product was dirty and contained other impurities. Furthermore, solar dryers can be used for household purposes [25]. Moreover, different types of solar dryers and covering materials were compared for drying blackberry pulp. The results showed no significant differences of chemical composition after different drying processes, except anthocyanins of dehydrated blackberry pulp was lower than the raw material [26].

Previous studies showed the temperatures inside the solar dryers were significantly different from the ambient temperatures and provided shorter drying times and higher quality dried products than that of open-air sun drying. In addition, the dried products were neither damaged by rain nor eaten by rodents and insects [7], [16]-[24]. Hence, solar drying technology has been used with good benefits.

Previous studies have proposed a variety of solar greenhouse dryers designed to meet particular drying requirements of specific products [16], [27]. There still exists a gap in research on solar greenhouse dryers for drying biodegradable material, especially for water hyacinth. Also, the basic drying parameters and the characteristics of dried products should be investigated.

Preliminary studies comparing solar dryer and natural sun drying methods have shown that the solar dryer method has better quality of dried product and shorter drying time than natural sun drying, but it has humidity control problems and differences in the drying rate in each level of the drying trays. Generally, the drying rate depends on the natural material characteristics, the solar dryer type, and the environmental factors during drying, such as temperature, air velocity, relative humidity, and heat transfer coefficient, among others [4], [28], [29].

Moreover, this project was designed to be in line with the Bio-Circular-Green Economy (BCG) Model of Thailand, which is a policy to drive economic development and improve the quality of life, based on environmental sustainability. The bedding production process transforms water hyacinth, which is a biodegradable waste within the community into an animal bedding product. The process of using solar greenhouse dryers to produce sun dried products creates economic value, reduces the import of materials, and generates income for the community using simple technology that the community can operate by themselves. Sun dried products have a reduced moisture content that inhibits microbial growth and use solar energy which provides a fuel cost-saving benefit. Sun drying has a zero-carbon footprint and produces no greenhouse gas emissions. Solar greenhouse dryers also provide an economical way for local communities and small business entrepreneurs to create a livelihood using sustainable natural resources. Furthermore, the product not only has the potential to be used as animal bedding but can also be produced as a biodegradable cushioning material to replace petroleum-based materials, as well as to reduce greenhouse gas emissions from foam or plastic manufacturing processes for environmental sustainability.

Accordingly, the objective of this research was to improve the efficiency of drying water hyacinth using a solar greenhouse dryer compared to traditional sun drying. The production of bedding material from dried water hyacinth was examined as an environmentally friendly way to create value from an invasive plant that is considered a nuisance. Additionally, the overall objective was to help create sustainable livelihoods for rural residents and small businesses by developing an economical solar dryer that can be used for production of dried water hyacinth and agricultural goods.

2. MATERIALS AND METHODS

2.1 Design and Construction of Solar Greenhouse Dryer

Figure 1 shows the shape and size of the solar greenhouse dryer and its sample positions. It was constructed and installed at the Community Enterprise Nara Phirom Group Network, Nakhon Pathom, Thailand. The solar dryer was positioned in an east-west orientation to collect more solar radiation in the solar dryer and optimize drying efficiency [15]. The dried water hyacinth was produced for use as animal bedding at the National Laboratory Animal Center (NLAC), Mahidol University. The solar dryer has a volume of 40.19 m^3 within a parabolic roof structure made of polycarbonate sheets. The parabolic structure was selected because its shape allows solar radiation pass into the dryer throughout the day. A parabolic shape also handles wind loads well. It is the main design of solar dryer structures of the Department of Alternative Energy Development and Efficiency, Thailand [4], [30]. Moreover, a recent study [31] reported that the parabolic-shaped solar dryer has higher efficiency, higher temperature, and shorter drying time compared with an even-span shape. The polycarbonate sheets were chosen because it is a transparent material with properties to create a good greenhouse effect. The material has high transmittance of shortwave solar radiation and low transmittance of infrared energy. Furthermore, it is lightweight and has good thermal resistance with low density and low thermal conductivity which reduces heat loss to the environment [7], [16]. The floor was made of 2-inch thick foam insulation sandwiched between black metal sheets providing strength, durability, and good heat absorption. Concrete posts were used to make an elevated platform due to this area being prone to flooding.

Fig. 1. The structure and dimension of a solar greenhouse dryer and sample positions (S).

The ventilation system consisted of three 6-inch fans, installed on the top of the solar dryer opposite to the air inlet, controlled by relative humidity sensors and powered by a 100-W solar cell panel with a 0.54 kWh battery for solar energy storage (Figure 2). The fans operated when the relative humidity inside the dryer was equal or higher than 60% and the ambient relative humidity was less than inside.

Relative humidity sensor controllers (MH13001, measurement error ±3% RH) and wet-dry bulb thermometers (red spirit filled thermometer measurement range 0 – 100 ºC) were installed both inside and outside of the solar dryer for inside and ambient temperature measurements. The crop temperature was measured by infrared thermometer (model DT8380, accuracy ±2%). The solar radiation intensity and air velocity were measured using a solar power meter (TENMARS model TM-206, accuracy ±10W/m^2) and a digital anemometer (AIMO model MS6252B, accuracy ±2%), respectively.

The dryer had two sets of metal shelves with four levels of drying trays. Trays were placed a distance of 0.40 m apart, inside the solar dryer. The dimensions of each drying tray were 1.25 m x 2.80 m x 1.40 m, allowing a maximum loading capacity of 100 kg of fresh water hyacinth (Figure 3). The product samples were weighed at 2-hour intervals using a digital balance (Digital balance DHL DJ1002C).

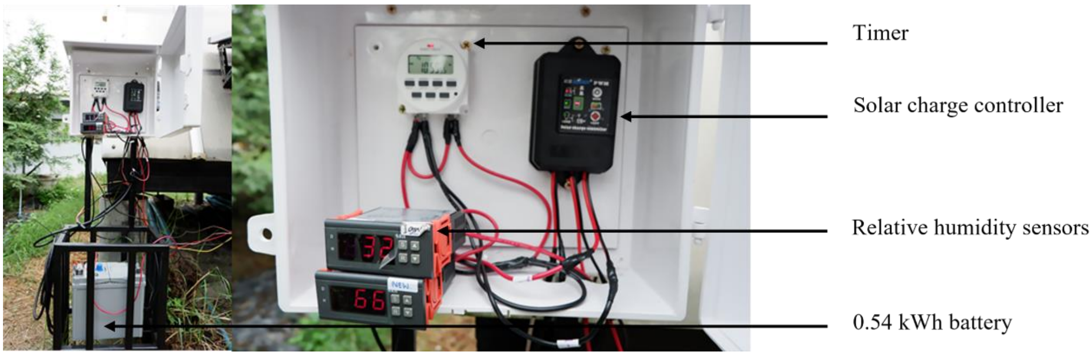

Fig. 2. Relative humidity control sensors.

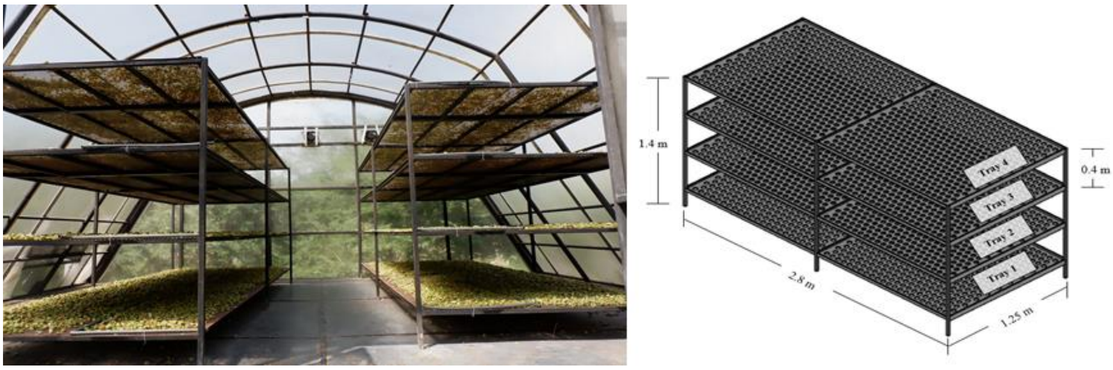

Fig. 3. The characteristic and dimension of the drying shelves.

2.2 Experimental Procedure

Comparison of the solar greenhouse dryer efficiency and natural sun drying was done under the same weather conditions. A total of three experiments (three replications) were carried out during the study from February to April in 2018. The water hyacinth was collected from Nara Pirom canal. After harvesting, their roots and leaves were chopped off. Only the stems were used as the main drying material. The stems were cleaned and cut into 1 centimeter lengths. Water hyacinth stems were selected based on a previous NLAC report that studied dried stems for use in animal bedding because dried stems had better shape, texture, and consistency than other water hyacinth parts.

For each experiment, one hundred kilograms of fresh water hyacinth were dried in the solar dryer. The study was conducted under two conditions. The first condition involved the natural sun drying experiment, in which the samples were divided into two groups. The second condition involved the solar greenhouse dryer experiment, in which the samples were divided into four main groups. Each group consisted of four levels of drying trays. One kilogram of fresh water hyacinth was assigned to each group. The samples were weighed at 2-hour intervals and returned to their same position. A sample was considered completely dried when its weight decreased to less than 85 grams, which is suitable dried product in terms of color and shape, following the criteria of the NLAC, Mahidol University. After a sample was completely dried, it was removed and replaced with a new sample on that tray. During the drying experiments, it was necessary to collect data on the variation of ambient temperature and relative humidity, temperature and relative humidity inside the solar dryer, solar radiation, and air velocity. Additionally, the variations of crop temperature and weight were recorded from 9:00 am until 3:00 pm.

Crop moisture content is the amount of water or liquid that is contained in the products. Normally, it is reported on a wet basis (wb) [3], [4], [29], [32]. The wet basis is the ratio of weight of water per weight of wet sample, which is calculated using Equation 1.

$$\%MC_{wb} = [(W_w - W_d)/W_w] \text{ x } 100 \quad (1)$$

where MC_{wb} is wet basis (%), W_w is wet weight (kg), and W_d is dry weight (kg).

2.3 Drying Efficiency

The drying efficiency of a solar greenhouse dryer is defined as the ratio of output energy of the solar dryer to input energy to the solar dryer which is shown as percentage. Solar radiation input on the dryer is calculated as shown in Equation 2 [7], [23].

$$E_{solar} = A_{dryer} \int S_r(t)dt \quad (2)$$

where E_{solar} is solar energy input on the solar dryer (J), A_{dryer} is dryer area (m^2), and $S_r(t)$ is solar radiation at time t (W/m^2).

Solar dryer output in terms of energy required for vaporization is calculated using Equation 3.

$$E_{dryer} = m_r L_g \quad (3)$$

where E_{dryer} is solar dryer output (J), m_r is moisture removed (kg), and L_g is latent heat of vaporization of moisture (J/kg).

Therefore, drying efficiency of the solar dryer is calculated using Equation 4.

$$\varepsilon_{eff} = [E_{dryer}/(E_{solar} + E_{module})] \times 100 \quad (4)$$

where ε_{eff} is solar dryer efficiency (%) and E_{module} is energy output from the solar panel (J).

3. RESULTS AND DISCUSSION

3.1 Performance of Solar Greenhouse Dryer

Three full scale experiments (three replications) were conducted to examine the performance of the solar greenhouse dryer from February to April in 2018. In the drying experiments, the solar radiation during drying of water hyacinth was measured. Figure 4 shows the variations of average solar radiation intensity. The first day was a clear day and solar radiation rose sharply from 9:00 am to 1:00 pm and the solar radiation intensity reached 973 W/m^2 (S.D.=45.13). However, it decreased considerably in the afternoon. Meanwhile, the second day exhibited fluctuations of solar radiation intensity. The solar radiation intensity in the morning (9:00 am to 11:00 am) reached a maximum of 892 W/m^2 (S.D.=35.35). However, it decreased considerably in the afternoon (1:00 pm to 3:00 pm) owing to cloudy skies. Both days of the experiment revealed similar patterns of solar radiation with the lowest intensity in the morning (9:00 am).

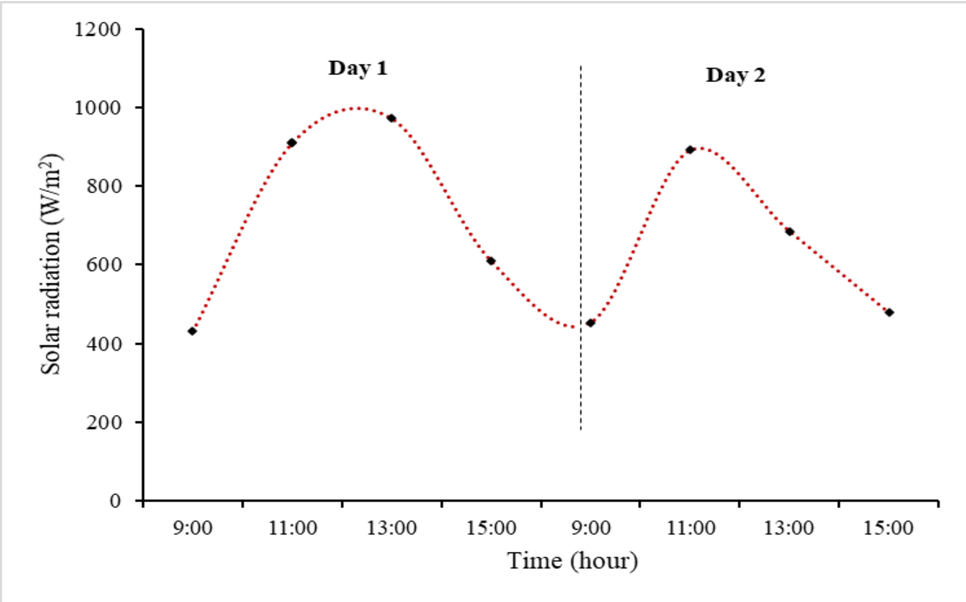

Fig. 4. Variation of solar radiation intensity with time of the day.

**The average of solar radiation intensity on 21-22 February, 2018 was 557 W/m^2, 17-18 March, 2018 was 792 W/m^2, and 9-10 April, 2018 was 688 W/m^2.*

Figure 5 shows the variations of average inside and ambient temperatures and relative humidity while drying the water hyacinth. On the first day, both the ambient temperature and temperature inside the solar dryer increased from 9:00 am to 1:00 pm, then decreased until the end of the study at 3:00 pm. On the second day, there were two periods with increasing temperature inside and outside the solar dryer, namely 9:00 am to 11:00 am and 1:00 pm to 3:00 pm. The maximum temperature inside the solar dryer and ambient temperature were 59°C (S.D.=3.46) and 38ºC (S.D.=2.47), respectively. The difference between the average temperatures inside and outside the solar dryer was approximately 14°C, a significant difference. The same finding was found in several previous studies [16], [17], [19]-[21], [23].

Meanwhile, on the first day, the relative humidity both within the solar dryer and outside ambient air decreased over time from 9:00 am to 1:00 pm. Lower relative humidity and higher temperatures enable the air to hold more water [16], [20]. In contrast, the reverse process occurred in the latter half of the day. The findings of this study were consistent with those of other studies [16], [17], [19], [20]. Weather conditions fluctuated the second day due to clouds. The relative humidity of the air inside and outside the solar dryer had two periods with decreasing relative humidity, namely 9:00 am to 11:00 am and 1:00 pm to 3:00 pm. The average relative humidity inside the solar dryer was approximately 12% less than outside. The relative humidity was inversely proportional to the temperature. Therefore, the environment inside the dryer had higher drying potential with consistently higher temperature and reasonably lower relative humidity than the ambient air. This is due to the polycarbonate sheets covering the solar dryer structure and removal of moist air inside the dryer by the humidity control system. Generally, the thermal radiation was absorbed by the drying material and the black elements inside the solar dryer. In addition, long wavelength infrared radiation is not reflected through the polycarbonate sheet, thus reducing heat loss to the outside and creating a greenhouse effect [7], [16], [33].

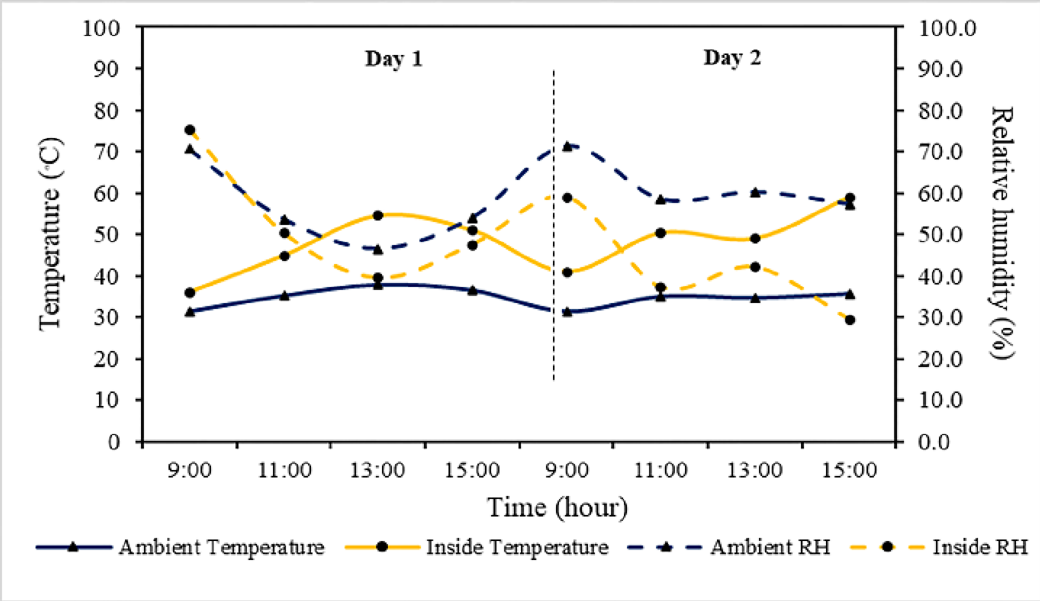

Fig. 5. Variation of temperatures and relative humidity during the day.
**The experiments were carried out on 21-22 February, 2018, 17-18 March, 2018, and 9-10 April, 2018.*

The air velocity of the three ventilators was investigated during the drying experiment. They were controlled by the relative humidity control sensors. The ventilators were in use starting from 9:00 am on the first day because the relative humidity inside the solar dryer was higher than the outside air. The ventilators had an average wind speed of 1.71 m/s (S.D.=0.10) and the ventilation rate of the solar dryer was 112 m^3/h. In contrast, the ventilators did not work all day on the second day due to the working condition of relative humidity control sensors. A previous study on drying water hyacinth in a hot air oven found that the optimum air flow rate was 158.4 m^3/h at 90ºC [28].

Figure 6 shows the comparison of average inside and outside crop moisture contents (% wet basis). The samples were placed on each level of the drying trays inside the solar dryer and outside for natural sun drying where they were exposed to the variation of the weather conditions. The crop moisture measurements indicated that the initial moisture content of water hyacinth samples in each experiment was approximately 92%. The samples placed on tray 4 (top tray) and tray 3 finished drying (sample weight less than 85 grams) at 11:00 am and 1:00 pm on the second day, respectively, with a 13% final moisture content. While the samples drying on tray 2, tray 1 (bottom tray), and natural sun drying reached a suitable moisture content of 20% at 3:00 pm on the second day. In comparison to the preliminary experiments, the drying time decreased ½ - 1 day by installing the relative humidity control sensors.

There were significant differences between the products dried inside and outside the solar dryer, as well as between the products in the different levels of the drying trays in the solar dryer. The samples on tray 4 have the greatest tendency to lose moisture content because the top tray received energy from both solar radiation and heat in the solar dryer. Furthermore, it also evaporated quickly because it was positioned close to the ventilator, suggesting better air flow and more efficient drying of sample product on the upper tray [7]. In comparison of the dried product properties between solar greenhouse dryer and natural sun drying process, it was noted that the dried products were different due to the variation of weather conditions and environmental factors.

Although the drying time of water hyacinth inside the greenhouse was only slightly different from that of natural sun drying, it can be clearly noticed that the physical quality of dried water hyacinth samples by solar dryer and natural sun drying processes had different characteristics. Figure 7 displays the color and shape of dried water hyacinth by solar dryer and the traditional sun drying methods. The dried water hyacinth from the solar dryer showed better appearance in terms of color and shape with pale white color, and smooth, and soft texture. In contrast, the natural sun drying method had green color with dark spots and shrinkage. The accumulation of heat inside the solar dryer enables moisture to evaporate continuously. On the other hand, the natural sun drying depends on external weather conditions, resulting in discontinuous moisture evaporation. Besides improving the product quality and reducing drying time, the solar greenhouse dryer offers considerable prevention of contamination by other foreign materials, such as dust and insects.

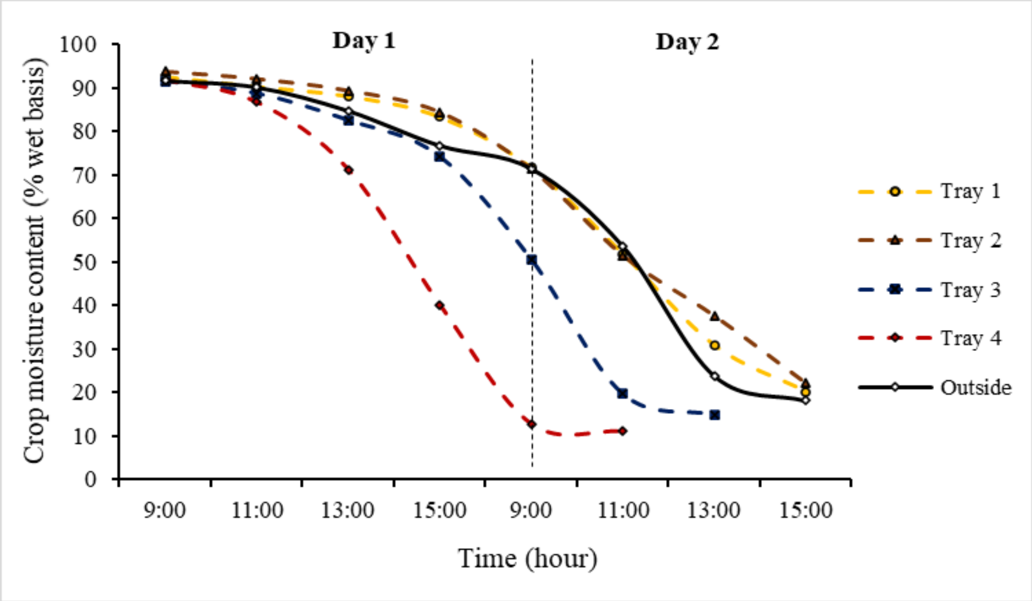

Fig. 6. Removal of water hyacinth moisture content (% wet basis) over time.
**The experiments were carried out on 21-22 February, 2018, 17-18 March, 2018, and 9-10 April, 2018.*
***Statistically significant difference at p = 0.05, with Sig. value = 0.010.*

(A) **(B)**

Fig. 7. Comparison of dried water hyacinth characteristics for solar greenhouse dryer (A) and natural sun drying (B).

During the drying experiments, there was a need to manage the position of the water hyacinth due to the obvious difference of drying rate on each tray. In this study, when a sample was considered completely dried, it was removed and replaced with a new sample on that tray. The study indicated that the crop loading could be increased by 50 kg within 3 days and decreased the drying time by ½ day for drying 150 kg of fresh water hyacinth.

The solar greenhouse dryer had an overall drying efficiency up to 63% for 100 kg of fresh water hyacinth. In comparison, Janjai and co-workers [7] found that the drying efficiency is related to the crop weight in the drying process. They reported the highest load capacity of 150 kg had the best drying efficiency of 20%. Therefore, the solar dryer was recommended to be run at the highest possible efficiency. In the study of Boonyasri and co-workers [34], the solar greenhouse dryer had a maximum efficiency of 56% for drying 40 kg of pork. The comparison of solar dryer and traditional sun drying efficiency are summarized in Table 1.

3.2 Cost Evaluation

Table 2 shows the costs and economic parameters of this solar greenhouse dryer for a small community in the study area. The cost evaluation is based on the recent prices of the materials and dried product. The solar dryer capacity is 100kg of fresh water hyacinth and the capital cost for installation and construction was 2,991 USD. The Community Enterprise Nara Phirom Group Network can produce 1,200 kg of dried water hyacinth per month for the NLAC which can generate income for the community of around 2,513 USD/month. Based on the costs to build the drying system and the income generated by the sale of the dried products, this solar dryer has an estimated payback period of 1.5 months.

Table 1. Summary for solar greenhouse dryer efficiency compared with natural sun drying for water hyacinth.

Parameters	Solar dryer	Natural sun drying
Loss of moisture content (% wet basis)	75	75
Solar radiation range (W/m^2)	430-973	430-973
Temperature range (°C)	36-59	31-38
Relative humidity range (%)	29.4-75.4	46.6-71.4
Minimum drying time (days)	1½	2

Table 2. Cost evaluation of the solar greenhouse dryer for community.

Items	Costs
Materials of constructions of the solar greenhouse dryer	1,496 USD
Polycarbonate plates	1,017 USD
Solar panel, fans, and relative humidity sensors	150 USD
Labor cost for constructions of the solar greenhouse dryer	299 USD
Repair and maintenance costs	1%
Sale price of dried water hyacinth	2.1 USD per kg
Expected life of the dryer	15 years

*Remark: *1USD = 33.43 Baht*

4. CONCLUSION

This study demonstrated the potential of a humidity controlled solar greenhouse for drying water hyacinth. The system has a maximum overall drying efficiency of 63% for 100 kg of fresh water hyacinth. The introduction of relative humidity controllers to regulate air flow through the solar dryer not only decreased the product drying time but also increased the batch load of water hyacinth by 50%. Moreover, potential customers preferred the color and shape of the product from this dryer more than the product from natural sun drying. The solar dryer is inexpensive with a payback period estimated to be 1.5 months. This makes the solar greenhouse dryer a viable option for small businesses. Hence, this solar greenhouse dryer provides an efficient approach for drying due to the effectiveness of controlling environmental factors in the drying process, especially insect disturbance, dust contamination, and climatic conditions. Furthermore, methods used in this study can be used as a guideline to produce other products from dried water hyacinth, such cushioning material. In addition, the solar dryer is suitable for used in rural areas without the need to be connected to an electrical grid.

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NOMENCLATURE

MC_{wb}	wet basis, %
W_w	wet weight, kg
W_d	dry weight, kg
E_{solar}	solar energy input on the solar dryer, J
A_{dryer}	dryer area, m^2
$S_r(t)$	solar radiation at time t, W/m^2
E_{dryer}	solar dryer output, J
m_r	moisture removed, kg
L_g	latent heat of vaporization of moisture, J/kg
ε_{eff}	efficiency of the solar dryer, %
E_{module}	energy output from the solar panel, J

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