# Experimental Performance and Auto-Regressive with eXogenous Input (ARX) Modelling of an Anti-UV Polycarbonate Sheet-covered Solar Dryer Equipped with a Control System for Drying Para Rubber Sheets

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**Abstract**

This paper presents the experimental performance and ARX modelling of an anti-UV polycarbonate sheet-covered solar dryer equipped with a control system for drying para rubber sheets. The dryer was built at Silpakorn University (13.82ºN, 100.04ºE), Nakhon Pathom, Thailand. This dryer comprises a roof structure covered by anti-UV polycarbonate sheets, shelves for hanging the rubber sheets, concrete floor, ventilation system and drying control system. The control system comprises temperature and relative humidity sensors and an on-off controller of the ventilating fans. The dryer is a medium size of a large-scale greenhouse type which has a length of 12.4 m, a width of 8.0 m and a height of 3.5 m and it can be used to dry 500 para rubber sheets, each of which has a dimension of approximately 0.46 m × 0.90 m × 0.005 m. The experimental results revealed that the moisture content of the sheets can be reduced from 30% w.b. to the final value of 1% w.b. in 3 days and the control system functioned as it was designed. In addition, the polycarbonate sheets can protect para rubber sheets from UV solar radiation and high quality dried rubber sheets are obtained. Based on the drying experiments, the dryer was modelled using the ARX approach. It was found that the model predicted well moisture content of the rubber sheets dried in this dryer.

**Keywords:**

*Solar Drying, Para Rubber Sheet, Greenhouse Dryer, Control System, ARX Modelling*

## 1. Introduction

Para rubber is an economically important crop of Thailand, with its growing areas of 21,735 km$^2$ [1]. Latex from para rubber trees is generally transformed into rubber sheets and cups. The rubber cups require less cost for the transformation but their sell price is relatively low. The rubber sheets need more manpower and materials for the transformation. However, the sheets can be sold at a higher price both in domestic and international markets. The main exported rubber of Thailand is still in the form of rubber sheets. Production of rubber sheets commonly requires drying processes by which the moisture content of the sheets is reduced to less than 5% d.b. [2]. The common practice of drying methods in Thailand are air drying and smoked drying. For the smoked drying, it is not only the reduction of moisture; smoked drying help to preserve the sheets. However, smoked drying needs fuelwood which is costly and creates problems of air pollution. For air drying, it generally needs natural sun drying for one day and followed by 2-10 days in-shade air drying [3]. During the natural sun drying, the sheets may be damaged by rain.

As Thailand is located in the tropics, which receives abundant solar radiation [4], the potential to dry rubber sheets with solar energy is relatively high. During the past 30 years, a number of researchers have proposed different types of solar dryers for drying rubber sheets in Thailand. The example of solar dryers proposed by these researchers are presented as follows.

Hassadin and Pongtornkulpanich [3] developed a solar-biomass drying system for drying para rubber sheets. The system is composed of a 948 $m^2$ - solar collector, a biomass burner and a drying chamber. The system uses solar energy for the period from 9:00 – 17:00 and out of this period, the biomass burner is employed to supply heat to a drying chamber of the system. The system could dry 100 para rubber sheets with a total weight of 135.20 kg. The system was tested for drying 100 rubber sheets. Based on the experimental results, the authors concluded that the para rubber sheets dried in this dryer got the better quality and shorter drying time as compared to those of the natural sun drying and smoked drying.

Jeentada et al. [5] proposed a cabinet type solar dryer. It consists of a 3.51 $m^2$ - flat plate solar air heater and a small box type drying cabinet. The cabinet can be used to dry 40 rubber sheets. The ventilation was provided by 3 DC fans powered by a solar cell module. Results from drying experiments revealed that the rubber sheets can be dried to the final moisture content of 1% d.b. within 7 days, and good quality of dried rubber sheets was obtained.

Jeentada et al. [6] developed a small solar dryer for drying para rubber sheets using hot air from a solar collector placed on top of the drying chamber. The speed of drying air varies in three steps, making drying air temperature and relative humidity varies accordingly. The dryer can be used to dry 30 rubber sheets and the drying time was 6-8 days.

The literature review observed that most proposed dryers for rubber sheets are indirect solar dryers, meaning that solar heat was used through solar collectors. This may be because ultraviolet (UV) radiation in solar radiation causes a rupture of the polymeric chain in the sheets [7], thus damaging the sheets. In addition, they are small scale dryers that could not meet the demand of rubber farmers. To overcome this problem, we propose a large-scale greenhouse type solar dryer covered by anti-UV polycarbonate sheets with a high loading capacity (500 sheets). As too high a temperature can damage the sheets, and too high relative humidity causes too long drying time, it is necessary to control the temperature and relative humidity of the drying air. In this paper, a control system was developed and the experimental performance of the dryer equipped with this control system is presented. Additionally, a simulation model based on Auto-Regressive with eXogenous input (ARX) was created for this dryer and UV solar radiation inside the dryer was measured in order to justify the protection of UV by the polycarbonate cover.

## 2. Materials and method

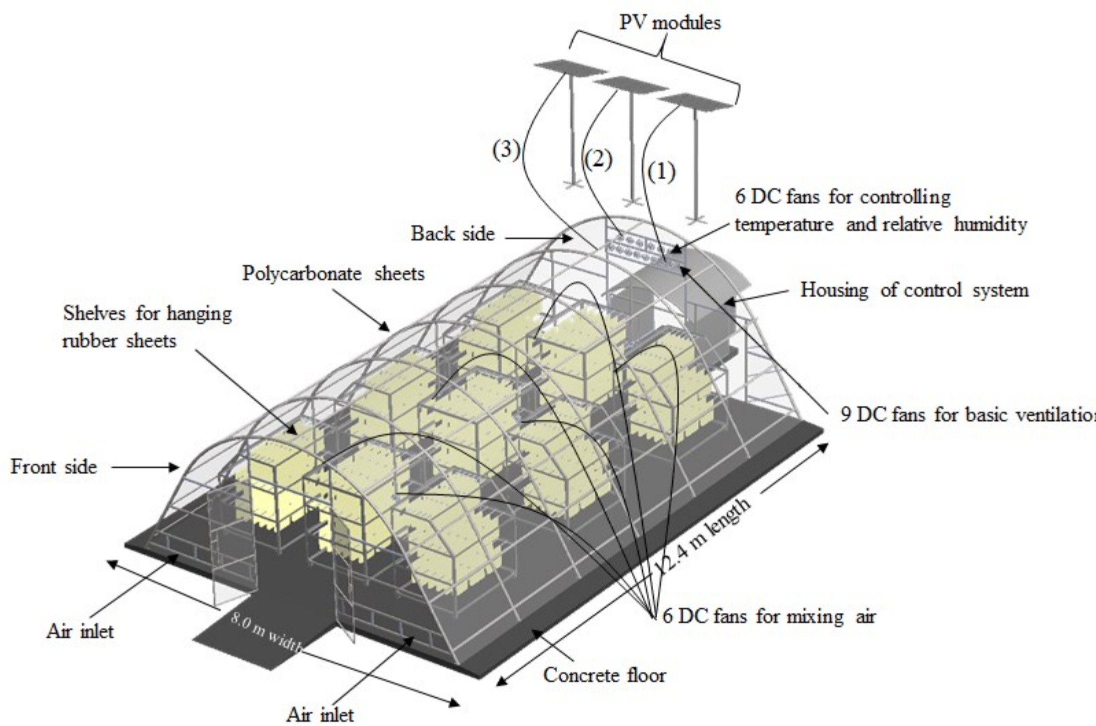
### *2.1. Rubber sheets*

The rubber sheets used in this study were obtained from a para rubber farmer in Ratchaburi located in the western part of Thailand. Latex from para rubber trees was processed to be rubber sheets by the para rubber farmer, and they were transported to the dryer for experiments in Nakhon Pathom (60 km from Ratchaburi).

### *2.2. Greenhouse solar dryer*

Large scale greenhouse solar dryers have been developed at Silpakorn University. This type of dryer has three sizes namely, small size, medium size and large size. In this study, a medium size of the large scale greenhouse dryer was modified and used to dry rubber sheets. This modified dryer is mainly composed of a roof structure covered by transparent double-layer polycarbonate sheets coated by anti-UV material, nine shelves for hanging the rubber sheets, a ventilation system and a concrete floor. The ventilation system is divided into three sub-systems (Fig. 1). The dryer has a length of 12.4 m, a width of 8.0 m, and a height of 3.5 m. The front and the back sides have a parabolic shape in order to reduce a wind load. The front side of the dryer has two air inlets, each of which has a rectangular shape with a width of 0.35 m and a length of 2 m. There is a door in the middle of the front side. This door is made of solid transparent polycarbonate sheets coated with anti-UV material. The schematic diagram and the pictorial view of the dryer are shown in Fig. 1.

The first sub-system consists of nine DC fans (14.4 W each) powered by three 60-W solar cells modules ((1) in Fig. 1(a)) for basic ventilation. The fans were placed at the backside of the dryer and used to suck moist air inside the dryer into the ambient environment. The sucking rate from this sub-system depends on the intensity of solar radiation. If the intensity of solar radiation is high, the sucking rate is also high and vice versa. The second sub-system has six DC fans (14.4 W each) for controlling drying air temperature and relative humidity through the control of the airflow. The fans, which are powered by two 60-W solar cell modules, are placed at the back wall of the dryer ((2) in Fig. 1(a)). The details of this sub-system are explained in the next sub-section. The third sub-system is used for mixing drying air and it comprises six DC fans (14.4 W each) powered by two 60-W solar cells modules ((3) in Fig. 1(a)). These fans are hung from the roof of the dryer to the space between the rows of the shelves for hanging the rubber sheets inside the dryer.




(a)

(b)

Fig. 1 (a) Schematic diagram of the dryer (b) Pictorial view of the dryer.

*2.3. Control system*

This system is called the second sub-system. It is mainly composed of a controller, battery with a charge controller, six DC fans and two 60-W solar cells modules. The controller is powered by a 30-W solar cell module with a built-in battery. The controller has temperature and relative humidity sensors. For the function of the controller, it receives the signal from temperature, and relative humidity sensors and the program inside the controller make the decision to send the output signal to the six DC fans. In this study, the controller is programmed to operate the fans when the drying air temperature is greater than 60ºC or relative humidity of the drying air is greater than 75%. Otherwise, the fans are stopped.

*2.4. Experiments*

A medium size of large-scale greenhouse type solar dryer was built at Silpakorn University, Sanamchandra Palace Campus (13.82ºN, 100.04ºE) in Nakhon Pathom, Thailand. The dryer has 9 shelves for hanging 500 sheets of para rubber. Each sheet has a dimension of approximately 0.46 m × 0.90 m × 0.005 m. In total, 600 kg of fresh rubber sheets can be dried in this dryer. The dryer was equipped with the controlled systems as described in section 2.2. In order to investigate its performance, various sensors were used to measure parameters affecting the performance of the dryer. A pyranometer (Kipp & Zonen, model CM11, ± 0.5% accuracy) was installed on top of the dryer to measure incident solar radiation on the dryer. Thermocouples (type K) were installed inside and outside the dryer to measure the drying air and ambient air temperatures, respectively. Hygrometers (Electronik, model EE23, ±2% accuracy) were employed to measure the relative humidity of the air inside and outside the dryer. Output signals from the pyranometer, thermocouples and hygrometers were captured every 10 minutes and recorded by a datalogger (Yokogawa, model DC100). Representative samples of rubber sheets were weighted every hour, and the weight data were used to determine the moisture content of the samples employing the oven method [8]. In this study, two drying experiments were carried out. The first experiment is for the performance evaluation and ARX modelling, while the second is for the ARX model validation.

The loading capacity of this dryer is 500 rubber sheets. According to our field survey, this capacity corresponds to the requirement of small para rubber producers. Therefore, for each experiment, the dryer was loaded with 500 rubber sheets in the morning, and they were dried continuously in the dryer until their moisture content was reduced to 1% w.b., then the experiment was stopped.

*2.5. Ultraviolet (UV) solar radiation*

The UV solar radiation inside and outside the dryer was measured using UV biometers (Solar Light, model 501A), as shown in Fig. 2. The output signals from these biometers were recorded by a data logger.

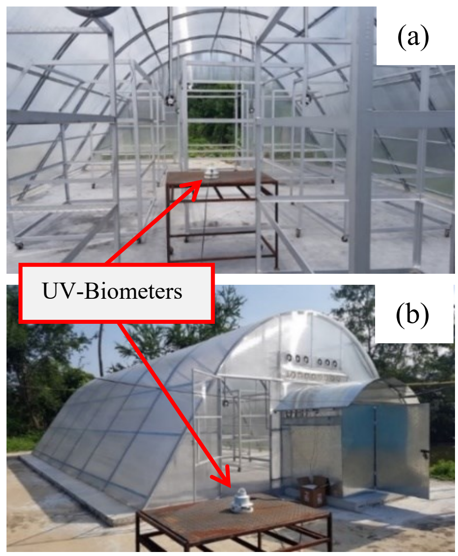



Fig. 2 Pictorial view of the measurements of UV solar radiation: (a) measurement inside the dryer and (b) measurement outside the dryer.

In addition, the capability of polycarbonate sheet in protecting UV solar radiation was also experimentally evaluated using a spectroradiometer (Instrument Systems, model Spectro 320-166).

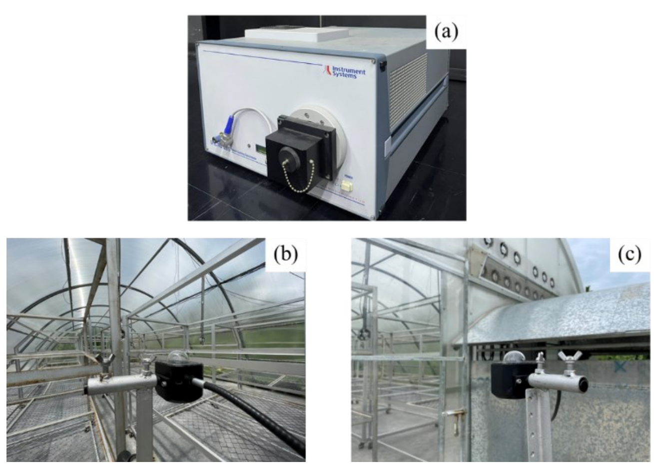



Fig. 3 Measurement of UV solar radiation using spectroradiometer: (a) Spectroradiometer (b) input optics of the spectroradiometer while measuring UV solar radiation inside the dryer (c) input optics of the spectroradiometer while measuring UV solar radiation outside the dryer.

### *2.6. Color of dried rubber sheets*

In this study, the color of dried rubber sheets dried in the dryer and dried with the natural sun drying was measured using a chromometer (HunterLab, model MiniScan EZ). The results are reported in the next section.

### *2.7. Performance of the control system*

During the drying experiments, the performance of the control system was observed whether it functioned as designed or not. The data on temperature and relative humidity of the drying air inside the dryer were recorded.

### *2.8. ARX modelling* [9]

Modelling is a powerful tool for developing a dryer as it allows developers of a dryer to assess the influences of drying parameters affecting the performance of the dryer. Nowadays, there are a number of modelling techniques, such as detailed physical modelling and modelling using ARX approach.

ARX modelling considers a system as a black box, and it does not require the knowledge of the physical process occurring in the system and it is based only on input and output data obtained from experiments or observations. In this study, ARX approach is chosen for the modelling.

In this study, ambient air temperature, ambient air relative humidity and solar radiation were selected to be input data of the ARX model. The output of the model is the moisture content of the rubber sheets dried inside the dryer.

According to the ARX approach, let $y(k\Delta t) = y_k$ be a sequence of output variable taken at a constant interval of time $\Delta t$, $u(t) = u_k$ is the corresponding input $u$. The Z-transform between the input and output sequence is written as:

$$A(Z)y(t) = B(Z)u(t) + e(t) \quad (1)$$

where Z is a delay operator, A(Z) is the coefficient of y(t), B(Z) is the coefficient of u(t) and e(t) is a sampling noise. Based on the results of the drying experiment, the following equations were obtained.

$$A(Z) = 1 - 0.1998Z^{-1} - 0.1406Z^{-2} - 0.1068Z^{-3} - 0.1856Z^{-4} \quad (2)$$

$$B1(Z) = -0.0601Z^{-1} + 0.02312Z^{-2} - 0.003616Z^{-3} + 0.02426Z^{-4} \quad (3)$$

$$B2(Z) = -0.01596Z^{-1} + 0.0004484Z^{-2} - 0.008742Z^{-3} + 0.02022Z^{-4} \quad (4)$$

$$B3(Z) = -0.0001793Z^{-1} - 0.000247Z^{-2} - 0.0003219Z^{-3} - 0.0001709Z^{-4} \quad (5)$$

The ARX model obtained from this study was used to predict the moisture content of para rubber sheets in the second experiment. Then, the predicted moisture content and the measured moisture content were compared. The root means square difference relative to the mean measured moisture content (rRMSD), and the mean bias difference relative to the mean measured moisture content (rMBD) [10] were used to indicate the performance of the ARX model.

### *2.9. Economic evaluation*

A method similar to Pankaew et al. [11] was employed to analyse the dryer for drying the rubber sheets economically using the economic and rubber data shown in Table 1.

Table 1 Economic and rubber sheets data used for the economic evaluation of the dryer.

| Items | Value |
|---|---|
| 1) Cost of the parabolic greenhouse dryer with the control system | 482,000 Baht |
| 2) Labor cost per batch for drying rubber sheets | 900 Baht |
| 3) Number of drying batches per year | 45 batches |
| 4) Drying time per batch | 3 days |
| 5) Quantity of fresh para rubber sheets per batch | 600 kg |
| 6) Quantity of dried para rubber sheets obtained from the dryer per batch | 400 kg |
| 7) Price of fresh para rubber sheets | 30.0 Baht·kg$^{-1}$ |
| 8) Price of dried para rubber sheets (good quality) | 55.0 Baht·kg$^{-1}$ |
| 9) Interest rate* | 5.75% |
| 10) Inflation rate* | 0.71% |
| 11) Life span of the dryer equipped with the control system | 15 years |

*Average values from the National Bank of Thailand in 2021 (1 USD = 32.8864 Baht)

## 3. Results and discussion

### *3.1. Experimental performance of the dryer*

The experiment carried out on 21-23 August, 2019 was used for demonstrating the performance of the dryer. During this experiment, solar radiation fluctuated due to clouds (Fig. 4), with the maximum solar radiation on the first day of 1200 W/m$^2$ (Fig. 4).

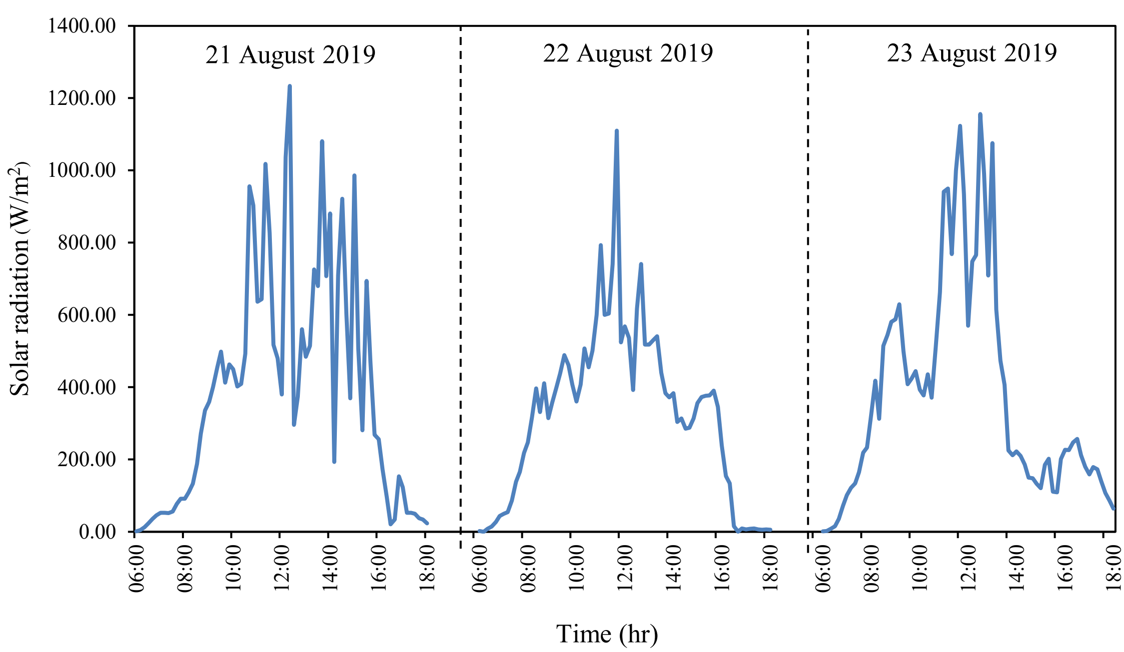



Fig. 4 Variation of solar radiation during the experiment.

The variation of drying air temperature was also fluctuated because of the fluctuation of solar radiation (Fig. 5). It was observed from Fig. 5 that the drying air temperature was higher than that of the ambient air. This higher temperature was likely due to the greenhouse effect exerted inside the dryer.

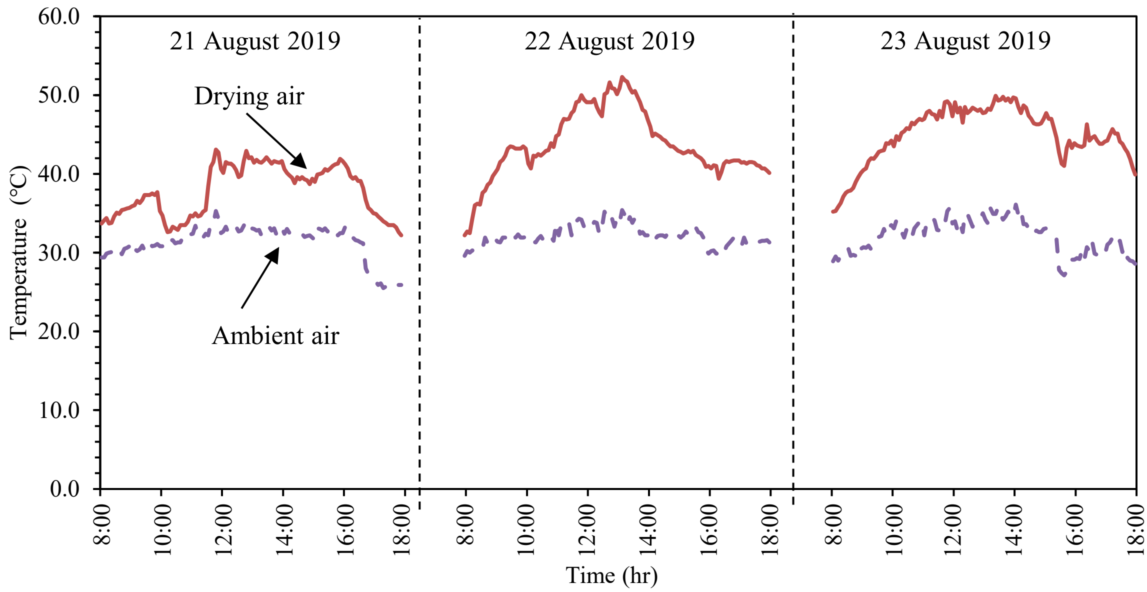



Fig. 5 Variation of the temperature of the drying air and ambient air.

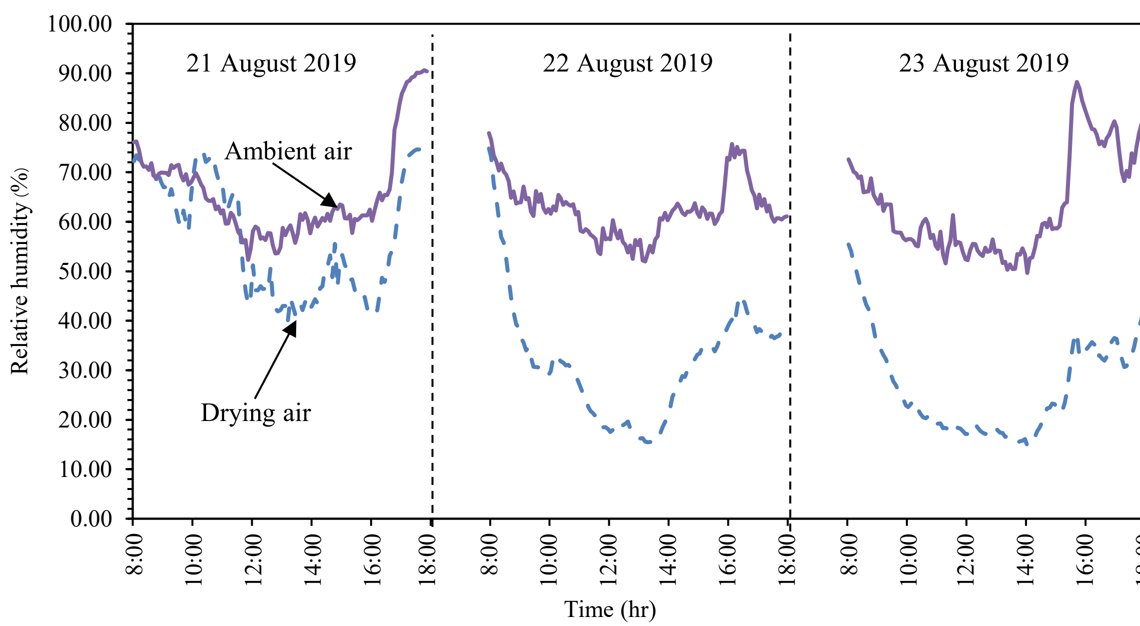



Fig. 6 Variation of the relative humidity of the drying air and ambient air.

For the relative humidity (Fig. 6), it was observed that it fluctuated, and its drying air values inside the dryer were lower for most of the time than that of the ambient air.

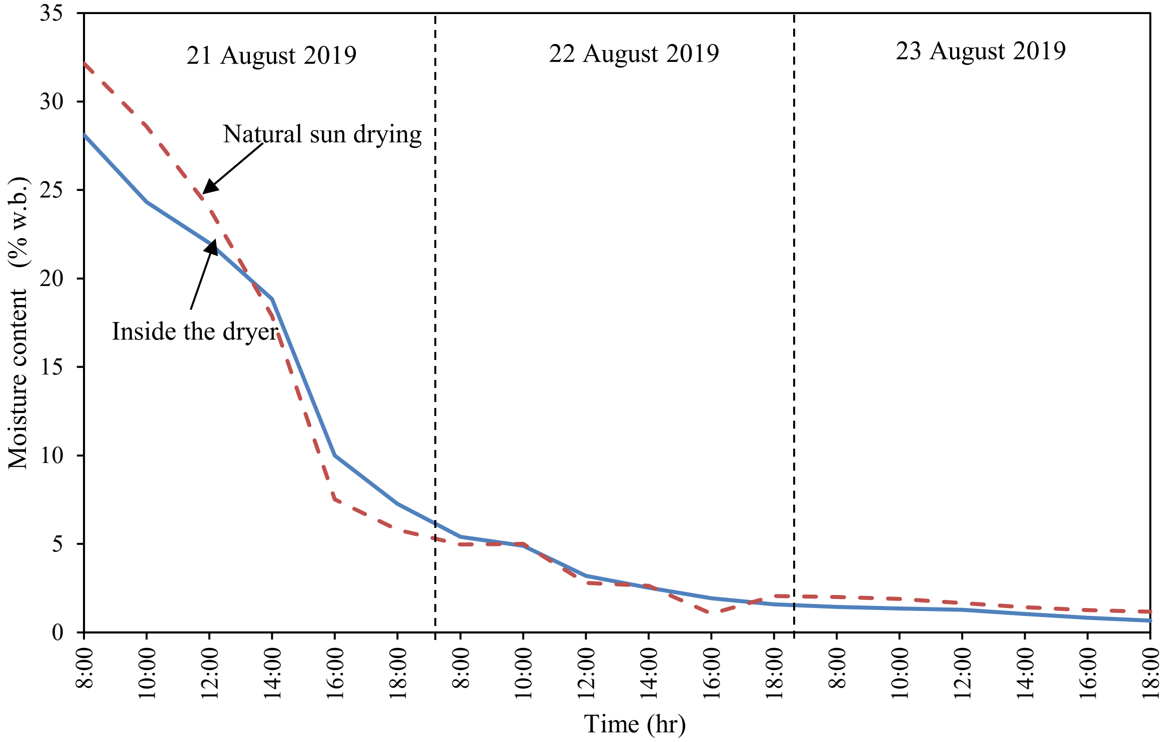



Fig. 7 Variation of moisture content of para rubber sheets drying in the dryer and dried with natural sun drying.

The pattern of the decrease in moisture content of the rubber sheets dried in the dryer and dried with the natural sun drying was quite similar (Fig. 7). This implies that the benefit of the solar dryer in terms of drying speed is low. However, the benefit in terms of color of dried sheets is much more valuable as the dryer protects the rubber sheets from UV solar radiation. This will be explained in sub-section 3.3 and 3.4.

*3.2. Result of the performance of the control system*

From the observation of the function of the drying system, it was found that the temperature of the air ($T_{drying}$) inside the dryer was always not greater than 60ºC and the relative humidity ($RH_{drying}$) of the drying air was always lower than 75%. When $T_{drying}$ > 60ºC or $RH_{drying}$ > 75%, the fans of the second sub-system start to operate, sucking air inside the dryer to the environment, lowering the temperature and relative humidity of the air. This indicates that the control system functioned as designed.

*3.3. Result of UV solar radiation measurement*

The results of UV solar radiation measurement using the biometers both inside and outside the dryer are shown in Table 2. The results of the measurement employing the spectroradiometer are depicted in Fig. 8.

Table 2 UV solar radiation inside and outside the dryer using biometers.

| Time and date of measurements | UV solar radiation (W/m²) | |
|---|---|---|
| | Inside the dryer | Outside the dryer |
| 12:00 h / 5 December 2019 | 0 | 0.186 |
| 12:00 h / 30 July 2021 | 0 | 0.154 |

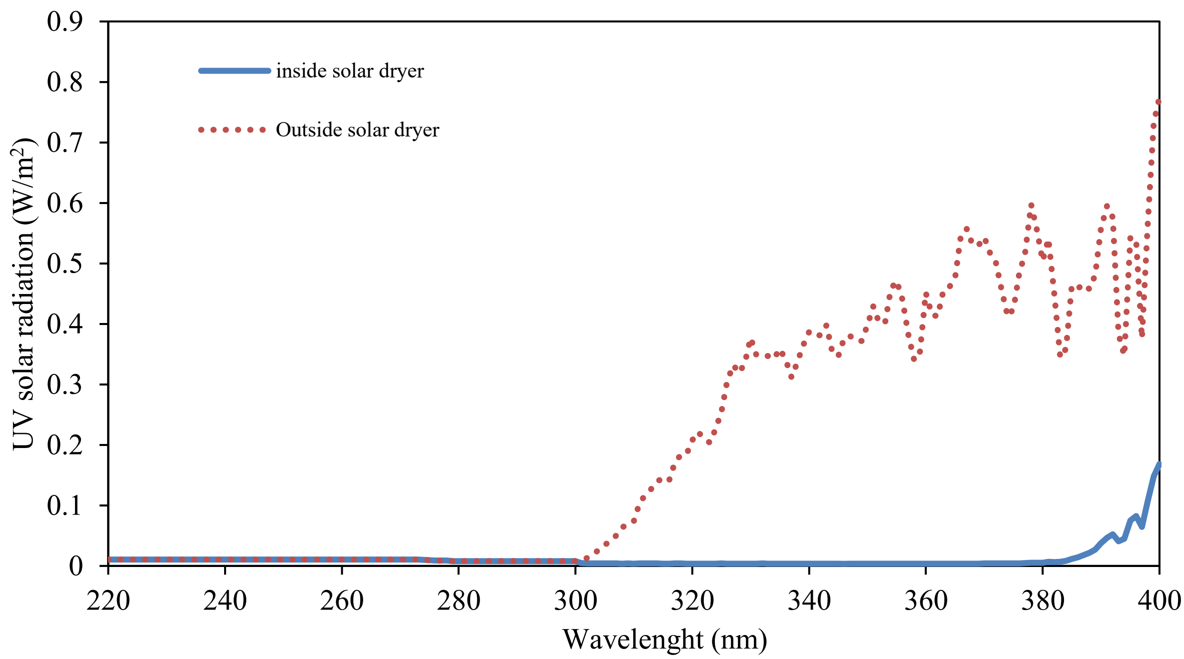



Fig. 8 Measurement of UV solar radiation using a spectroradiometer.

The results from UV biometers and spectroradiometers show that there is negligible UV solar radiation inside the dryer, making no adverse effect of UV on the rubber sheets.

*3.4. Result of the colour measurement*

The measurement results of the dried rubber sheets are shown in Table 3.

Table 3 Colour of the dried rubber sheets from the measurements.

| Drying method | Color parameters | | |
|---|---|---|---|
| | $a^*$ | $b^*$ | $L^*$ |
| **Natural sun drying** | 0.69 | 7.7 | 35.55 |
| **Dried in the dryer** | 1.62 | 10.94 | 33.09 |

It was found that the colour of the rubber sheets dried inside the dryer was bright yellow while the colour of the rubber sheets dried with the natural sun drying is dark yellow. This demonstrates that the dried rubber sheets obtained from the solar dryer have better colour (Fig. 9).

(a)

(b)

Fig. 9 Colour of dried rubber sheets: (a) dried inside the dryer (b) natural sun drying.

*3.5. Results of ARX modelling*

The ARX model based on the first experiment was used to predict the moisture content of the rubber sheets of the second experiment. It was found that the predicted moisture content and that obtained from the experiment are in good agreement with the rRMSD of 9.8% and the rMBD of 0.5%.

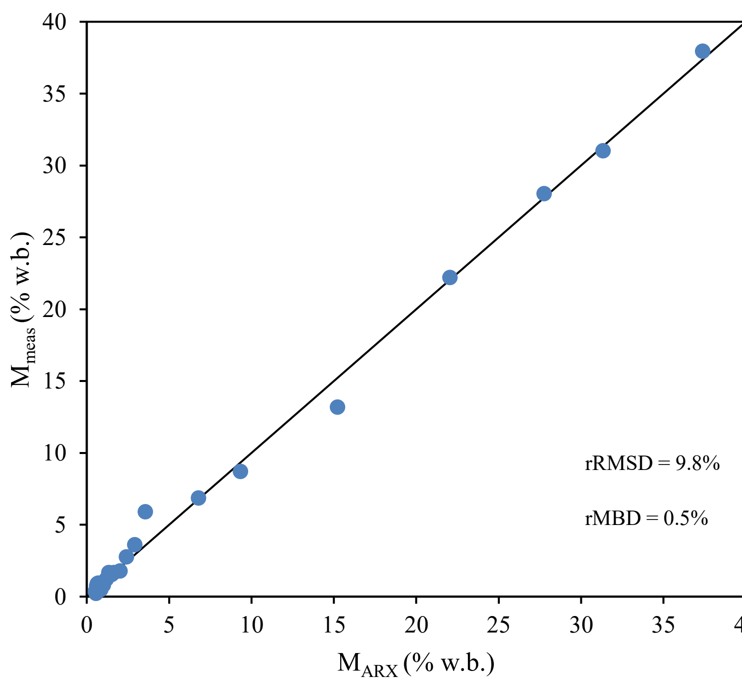



Fig. 10 Comparison between the moisture content from measurements ($M_{meas}$) and ARX modelling ($M_{ARX}$) (rRMSD is root mean square difference relative to mean measured value in percent and rMBD is mean bias difference relative to mean measured value in percent).

*3.6. Results of the economic evaluation*

From the economic evaluation of the dryer, the drying cost is found to be 33.7 Baht/kg and the payback period is 8.91 years, and the dried rubber sheets have no damages. At present, the Thai government has a subsidy program for those who want to invest in the dryer, and the subsidy is about 30% of the standard capital cost of the dryer. In this case, the drying cost becomes 33.1 Baht/kg, and the payback period will be 7.12 years.

Although its capital cost is almost free for natural sun drying, however, according to our field survey, approximately 20% of the rubber sheets were damaged during the drying. Additionally, poor quality of dried sheets is obtained. As a result, the drying cost for natural sun drying is approximately 40.4 Baht/kg. Therefore, the use of the greenhouse dryer offers better economic performance, as compared to that of natural sun drying.

## 4. Conclusion

The performance of a medium size large-scale greenhouse type solar dryer equipped with a control system was experimentally evaluated. It was found that the dryer functioned well and the dryer could be used to dry up to 500 rubber sheets. There is negligible UV solar radiation inside the dryer. In addition, a good quality of dried rubber sheets was obtained. The economic evaluation of the dryer with the governmental subsidy revealed that the drying cost for rubber sheets is 33.1 Baht/kg and the payback period is 7.12 years. The modelling results revealed that the ARX model could accurately predict the moisture content.

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## References

[1] CMGF Secretariat Thailand (2020). *An analysis of the economic situation of the southern region (rubber and oil palm) in 2020*. Prince of Songkla University (in Thai).

[2] Rubber Authority of Thailand (2017). *Production of good quality rubber sheets*. Retrieved July 1, 2021, from http://www.raot.co.th/ewt_dl_link.php?nid=4871.

[3] Hussadin, M., & Pongtornkulpanich, A. (2015). Solar-biomass drying system for para rubber sheet. *International Journal of Renewable Energy, 10*(1), 37-46.

[4] Janjai, S., Laksanaboonsong, J., Nunez, M., & Thongsathitya, A. (2015). Development of a method for generating operational solar radiation maps from satellite data for a tropical environment. *Solar Energy, 78*(6), 739-751.

[5] Jeentada, W., Phetsongkram, P., & Chankrachang, T. (2016). Drying of para rubber sheet using forced convection solar dryer. *Journal of science of Burapha University, 21*(1), 87-99 (in Thai).

[6] Jeentada, W., Jareanjit, J., & Tippracha, P. (2018). Drying experiment of rubber sheet using solar dryer with solar collector installed on top wall of the dryer. *The Journal of KMUTNB, 29*(1), 23-33 (in Thai).

[7] Breymayer, M., Pass, T., Mühlbauer, W., Amir, E.J., & Mulato, S. (1993). Solar-assisted smokehouse for the drying of natural rubber on small-scale Indonesian farms. *Renewable Energy, 3*(8), 831-839.

[8] Nielsen, S.S. (2010). *Food Analysis*, Fourth Edition. West Lafayette, IN, USA: Springer.

[9] Ljung, L. (2017). *System Identification Toolbox: Getting Started Guide*. Natick, MA, USA: The MathWorks, Inc.

[10] Iqbal, M. (1983). *An Introduction to Solar Radiation*. Academic Press, Toronto.

[11] Pankaew, P., Aumporn, O., Janjai, S., Mundpookhiew, T., & Bala, B.K. (2019). Performance of parabolic greenhouse solar dryer equipped with rice husk burning system for banana drying. *Journal of Renewable Energy and Smart Grid Technology, 14*(1), 52-65.