Study of Large-scale Solar Dryers Equipped with Monitoring and Control Systems for Banana Drying

Orawan Aumporn, Rungrat Wattan, Somjet Pattarapanitchai, Mongkol Sangsan, Serm Janjai[1,*]

Solar Energy Research Laboratory, Department of Physics, Faculty of Science, Silpakorn University, Nakhon Pathom 73000, Thailand

***Corresponding author's email:** serm.janjai@gmail.com

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Abstract

This paper presents a study on the field performance of 18 large-scale greenhouse solar dryers equipped with remotely controlled monitoring and control systems. The dryers were built for the dried banana producers in Phitsanulok province in Thailand. These dryers were equipped with monitoring and control systems that allowed remote monitoring of operation parameters such as the drying air temperature, drying air relative humidity, and the weight and images of the bananas being dried through a mobile phone. In addition, the on-off controls of the LPG burners and AC fans were also controlled via a mobile phone. To investigate the performance of each dryer, 1200 kg of peeled bananas was dried in it. Bananas dried inside the dryers dried much faster than those dried outside the dryers that were under ambient conditions. Remote control of the monitoring and control systems using a mobile phone, facilitated a more convenient and efficient utilization of the dryers. An economic analysis of the dryers was also carried out. The results showed that the drying cost was 49 THB/kg, the payback period (without subsidy) was 4.88 years, and the internal rate of return was 16%.

Keywords:

Solar Drying, Large-scale Solar Dryer, Banana, Monitoring and Control System, Mobile Phone

1. Introduction

Large-scale greenhouse solar dryer is one of the most widely used solar dryers for producing commercially dried products [1-4]. This is because this type of dryer has high loading capacity which meets the demand of dried product producers with reasonable investment cost. In addition, products being dried in the dryer is completely protected from rain and animals. Approximately 600 units of this type of dryer have been installed and used in Thailand and other Asian countries [1-4]. This type of dryer has various loading capacity for drying fruits and vegetables. There are four standard sizes, namely small size (loading capacity of 100-300 kg of fruits or vegetables), medium size (loading capacity of 400-600 kg), large size (loading capacity of 1000-1200 kg) and extra-large size (loading capacity of 1500-1700 kg). The selection of the size of the dryer depends on the quantity of product to be dried.

For bananas, the large size with the loading capacity of 1200 kg of peeled bananas is commonly employed. All sizes of this type of dryer consist of parabolic roof structure covered by transparent polycarbonate sheets, array of trays for placing the products, a ventilating system, and a concrete floor. The ventilating systems of the small and medium sizes consist of DC fans powered by PV-panels. As the length of the large and extra-large sizes is relatively high, apart from PV-panels, AC fans powered by electricity from grid are also used.

For banana drying in this type of dryer, users of the dryer usually walk inside the dryers to inspect the state of drying and drying air temperature inside the dryer is quite high, causing inconvenience for using of this type of dryer. To overcome this problem, the dryer can be equipped with a monitoring and control system so that users could inspect remotely the state of drying, and control LPG burners & AC fans, via a mobile phone. There will no need to enter the dryers to do monitoring.

During the past twenty years, several monitoring and control systems for various engineering systems have been developed. Examples of such systems are presented as follows.

Roman and Hensel [5] studied a system for real-time product moisture content monitoring in a batch dryer using psychrometric and airflow measurements. Their system consisted of two K-type thermocouples to measure drying air temperature. These measuring sensors were connected to a data logger and the data obtained were analyzed in a computer. The experimental results showed that the system was suitable for monitoring the moisture content.

Al-Ali et al. [6] applied the internet of things (IoT) system to a solar powered irrigation pump. The system utilized a single board system-on-a-chip controller which had a built-in WIFI and a solar cell panel was used to provide the required operating power. The controller read the signal from the sensor of the soil moisture, humidity and temperature sensors, and then appropriate command signals were sent to control the irrigation pump. The system had three modes of operation, namely control mode, mobile monitoring-control mode, and fuzzy logic-based control mode. The system was tested, and good results were obtained.

Dhere et al. [7] used the IoT for solar water pumping and drying systems. The IoT was employed to remotely monitor the systems using Zigbee and Global System for Mobile Communications (GSM) modules. The Zigbee sent data wirelessly from the control sensor and these data were transferred to the cloud system through the GSM module. These data can be seen in a mobile phone. From the test, it was found that the IoT system performed well.

2. Objective of the Study

The objective of the study is to investigate the field performance of large-scale greenhouse solar dryers equipped with the monitoring and control systems that are remotely controlled via mobile phone. At present, no work on the use of such monitoring and control systems for large-scale greenhouse solar dryers has been reported.

3. Materials and methodology

3.1. Drying of raw materials

The raw materials investigated in the study were bananas (Namwa variety). The bananas used for the drying experiments were purchased from northern Thailand and transported to Phitsanulok province (16.824 ºN, 100.258 ºE), Thailand. For all experiments, the bananas were ripened to approximately the same degree of ripeness and then peeled. The peeled bananas were spread as a thin layer on drying trays inside the large-scale greenhouse solar dryers. Another batch of peeled bananas was also spread outside the dryer for natural sun drying. This batch of bananas was the control variable in the experiment.

3.2. Large-scale greenhouse type solar dryer

Each large- scale greenhouse type solar dryer equipped with monitoring and control system consisted of a parabolic roof structure covered by transparent polycarbonate sheets, 6 arrays of product trays placed on raised-platforms, ventilating system, and concrete floor. The dryer had a width of 9 m, a length of 20.8 m and a height of 3.5 m. The front side had 2 air inlets, each of which had an area of 0.35×2.0 m^2, see Fig. 1. The back side was equipped with 10 DC fans (14.4 W each) and 6 AC fans (35 W each) for sucking moist air in the dryer to ambient environment. Each dryer had a loading capacity of 1200 kg of peeled bananas. The dryer was equipped with monitoring and control system, whose details are described in the next sub-section.

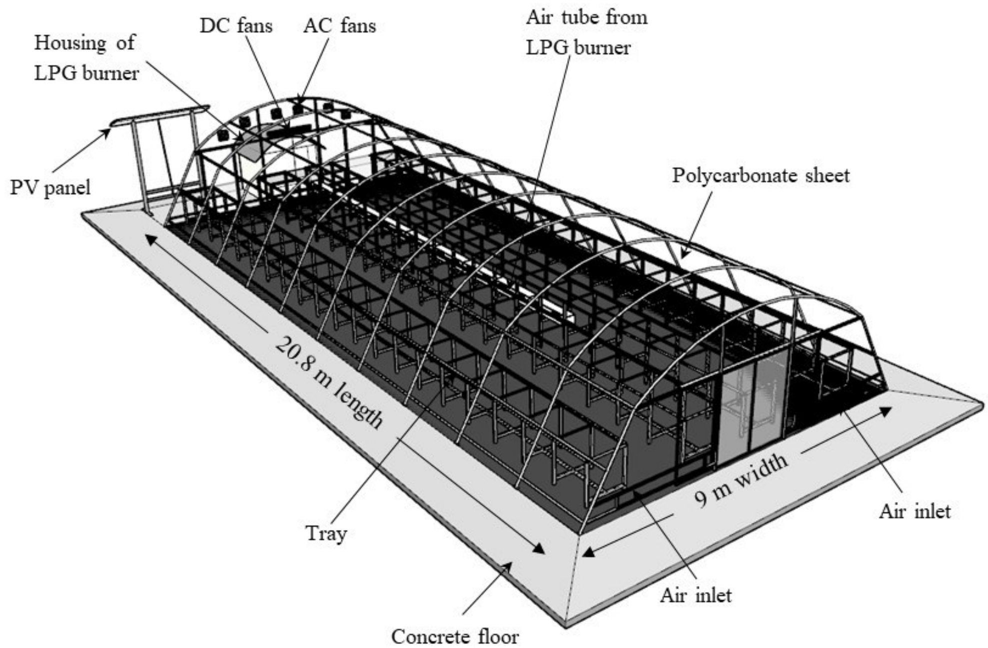

Fig.1 Structure of the large-scale greenhouse type solar dryer.

3.3. Monitoring and control system

Each monitoring and control system consisted of a temperature & relative humidity sensor (AOSONG, model AM2301 DHT11), weight sensor (loadcell, GUANG, model YZC-1B), USB camera (ELP, model USBFHD06H), and controller of the gas burner and AC fans. Output analog signals of these sensors were sent to the system of monitoring and control. The system sent the digital signals to the internet via WIFI, see Fig. 2.

A mobile application (App) was created for a mobile telephone to enable the telephone to access the data from the dryers and to send the control command via the internet to the dryer. A dryer user had to install an application called “Parabola 4.0” see Fig. 3(a). To use the application, the user had to sign up, see Fig. 3(b) to an application account. After creating an account, the user was able to follow the drying condition using the mobile telephone and was also able to control the LPG burner and AC fans, see Fig. 3(c).

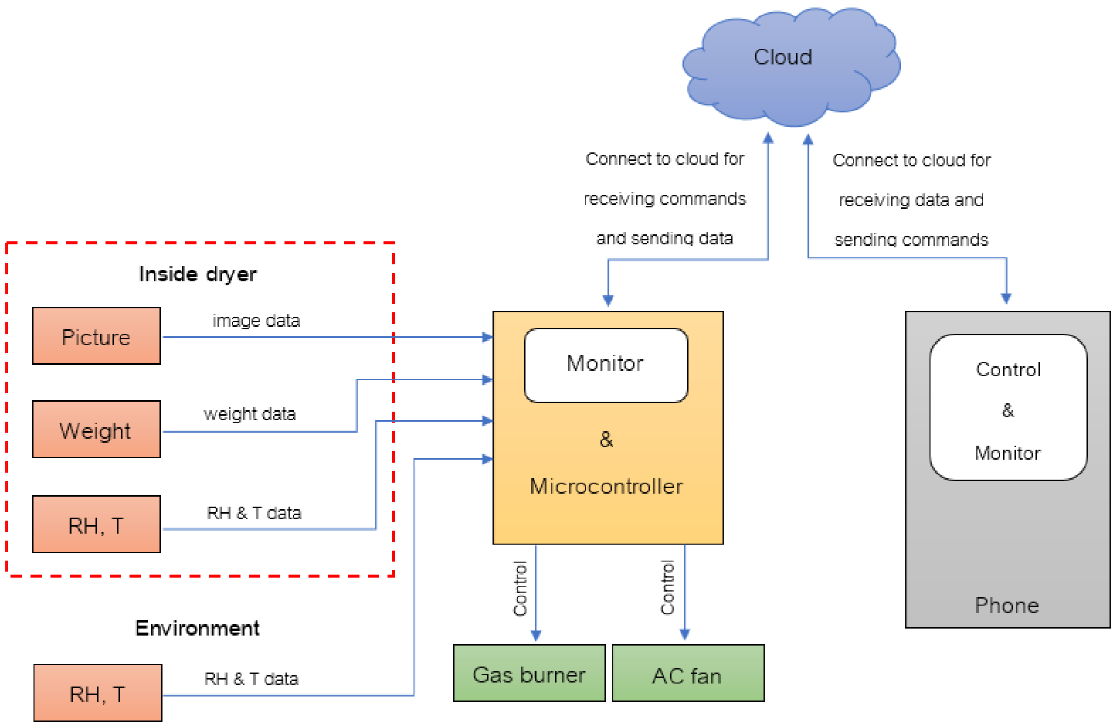

Fig. 2 Diagram of the monitoring and control system
(RH & T are relative humidity and temperature, respectively).

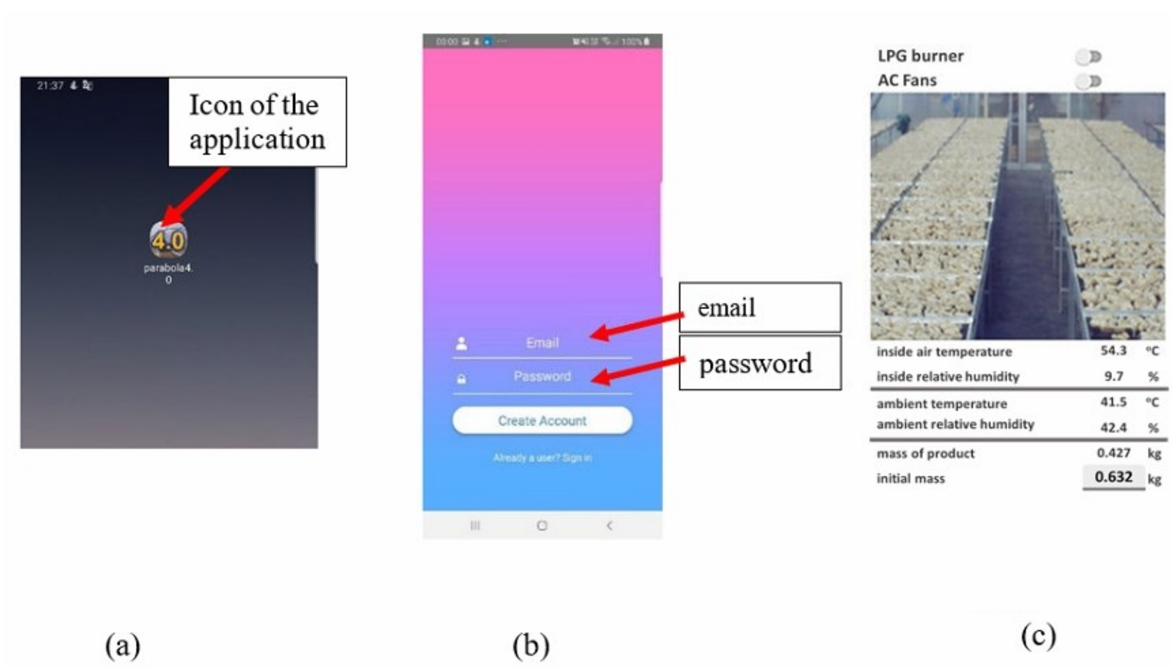

Fig. 3 Application screen on a mobile phone (a) icon of the application (b) sign up screen (c) screen for monitoring drying parameters and controlling the gas burner and AC fans.

3.4. Experimental performance evaluation

3.4.1 Thermal performance of the dryers

Eighteen large-scale greenhouses type solar dryers equipped with the monitoring and control systems were built in Phitsanulok province (16.824 ºN, 100.258 ºE), Thailand, see Fig. 4. Field experiments were carried out at these dryers. The purposes of the experiments were to observe the thermal performance of each dryer and to observe the performance of the monitoring and control system. Dates of experiment for each dryer are shown in Table 1.

Table 1 Dates of experiment.

Number of the dryer	Dates of experiment
1	19-22 June 2020
2	14-19 August 2020
3	30 August – 1 September 2020
4	3 – 7 August 2020
5	19 – 22 June 2020
6	3 – 5 July 2020
7	14 – 16 July 2020
8	28– 30 June 2020
9	8 – 10 September 2020
10	15 – 18 July 2020
11	8 – 11 September 2020
12	16 – 20 August 2020
13	10 – 14 August 2020
14	15 – 19 August 2020
15	27 – 29 August 2020
16	26 – 28 August 2020
17	4 – 8 August 2020
18	16 – 20 August 2020

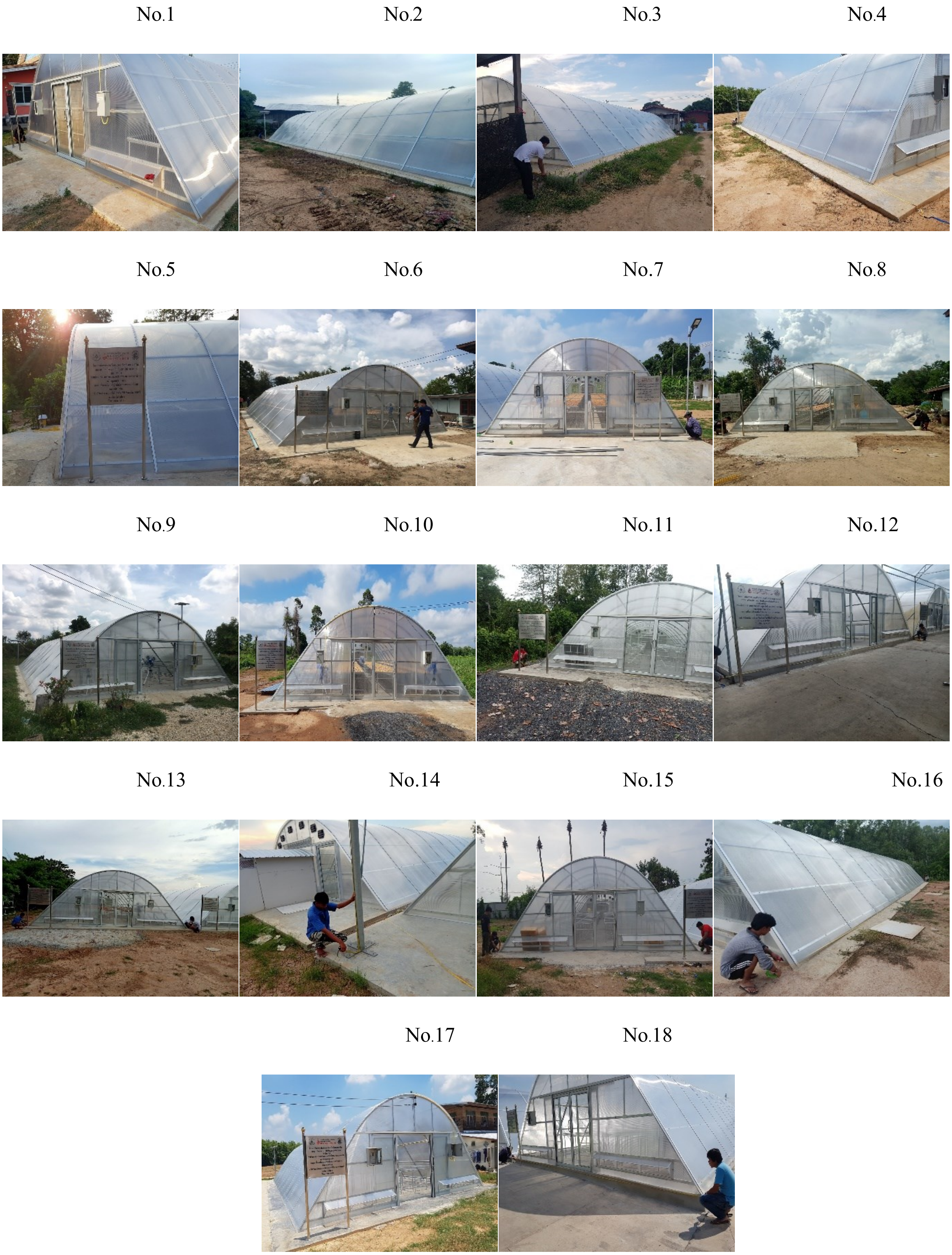

Fig. 4 Pictorial view of 18 large-scale greenhouse solar dryers built in this study.

Each dryer was used to dry about 1200 kg peeled bananas. Parameters affecting the performance of the dryer were measured. Solar radiation incident on the dryer was measured by a pyranometer (Kipp & Zonen, model CM11, accuracy ± 0.5%). Drying air and ambient air temperatures were measured using K-type thermocouples (± 2% accuracy). Relative humidity of drying air and ambient air were measured by using hygrometers (Electronik, model EE 23, ± 2% accuracy). Representative samples of bananas at different positions inside the dryer were periodically recorded at 1-hour interval using a digital balance (Kern, model 474-42, accuracy ± 0.1 g).

For each dryer, the output signals from the pyranometer, thermocouples and hygrometers were recorded in a multichannel datalogger (Yokogawa, model DC100). To compare the performance of the dryer with natural sun drying, a sample of bananas to serve as experiment control was also dried outside the dryer under the same weather condition as that of the bananas dried in the dryer. At the end of the drying experiment, the solid mass of the dried banana products was determined by drying again in an electric oven at 103ºC for 24 hours.

The drying experiments for all dryers were not carried out at the same day because these experiments were aimed to observe the performance of each individual dryer, and not for performance comparison. The performance of the monitoring and control system of each dryer was also observed during the experiments. The drying air temperature, the drying air relative humidity and the drying curve were the parameters used to indicate the thermal performance of the dryers.

3.4.2 Performance of the monitoring and control system

The 18 solar dryers were equipped with the monitoring and control systems and during the drying experiments, these systems were tested by accessing the experimental data using a mobile phone.

The results are shown in the next section. Had it rained or the drying air temperature had been equal or lower than 40ºC on the first day of the drying, the user of the dryer could send a command via a mobile phone to turn on the gas burner. Additionally, had the drying air temperature been higher than 60ºC, the user could also send a command via the phone to turn on the AC fans.

3.5. Water activity measurement

The water activity of dried bananas was measured by using a water activity meter (Rotronic, model HC2-AW). Samples of dried bananas were taken from the dryer. The value of water activity from these samples are presented in the next section.

3.6. Economic analysis

Three economic parameters were evaluated. These were drying cost, payback period, and internal rate of return. The details of the analysis are described as follows.

1) Drying cost

The capital cost of the dryer (C_T) consisted of the cost of the dryer (C_{dryer}) and the cost of the monitoring and control system ($C_{monitor}$).

$$C_T = C_{dryer} + C_{monitor} \quad (1)$$

The annual cost of the dryer, equipped with the monitoring and control system (C_{annual}), was calculated from the equation below (by Audsley and Wheeler [8]):

$$C_{annual} = \left[C_T + \sum_{i=1}^{N} (C_{main,i} + C_{op,i})\omega\right] \left[\frac{\omega - 1}{\omega(\omega^N - 1)}\right] \tag{2}$$

and

$$\omega = (100 + i_{in})/(100 + i_f) \tag{3}$$

where $C_{main,i}$ and $C_{op,i}$ are the maintenance cost and operating cost for year i, respectively. i_{in} and i_f are interest and inflation rates, respectively. The maintenance cost was estimated to be 1% of the capital cost.

The operating cost consisted of labor cost for processing fresh and dried bananas, the cost of a manpower for looking after the dryer (C_{labor}), the electricity cost for operating the AC fans ($C_{electricity,fan}$), electricity cost for monitoring and control system ($C_{electricity,control}$) and the cost of the internet ($C_{internet}$). The operating cost can be determined using the equation below:

$$C_{op,i} = C_{labor} + C_{electricity,fan} + C_{electricity,control} + C_{internet} \tag{4}$$

The electricity cost for AC fans can be calculated from the unit cost of electricity ($C_{unit\_electricity}$) and the amount of electricity consumed by the fans per year ($M_{electricity,fan}$), as follows:

$$C_{electricity,fan} = C_{unit\_electricity} \times M_{electricity,fan} \tag{5}$$

The cost of electricity for the monitoring and control system ($C_{electricity,control}$) was calculated from the unit cost of electricity and the amount of electricity consumed for the monitoring and control system ($M_{electricity,control}$) as follows:

$$C_{electricity,control} = C_{unit\_electricity} \times M_{electricity,control} \tag{6}$$

The drying cost (Z) was computed from the annual cost (C_{annual}) and mass of dried banana produced per year (M_d) as:

$$Z = \frac{C_{annual}}{M_d} \tag{7}$$

2) *Payback period (PB)*

This economic parameter was calculated from the following equation [9].

$$PB = \frac{C_T}{M_d P_d - (M_f P_f + M_d Z)} \tag{8}$$

where M_f and M_d are the mass of fresh bananas used per year and dried bananas obtained per year, respectively, and P_f and P_d are the price of fresh bananas and dried bananas, respectively.

3) Internal rate of return (IRR)

IRR was calculated using the following formula given by Park [10]:

$$\sum_{i=1}^{N} \frac{C_i}{(1 + IRR)^i} = 0 \qquad (9)$$

where C_i is the cash flow at year i for the dryer equipped with monitoring and control system, and N is the life span of the dryer. The data used for the economic analysis is given in Table 2.

Table 2 Cost data.

Name of parameters	Value
Cost of the dryer	850,000 THB***
Cost of the LPG burner	50,000 THB
Cost of the IoT system	50,000 THB
Internet cost	1200 THB/year
Electricity cost for monitoring and control system	1600 THB/year
Cost of LPG gas	400 THB/batch
Quantity of fresh banana	1200 kg/batch
Price of fresh banana	20 THB/kg
Cost of labor (4 persons)	8000 THB/batch
Quantity of dried banana	700 kg/batch
Price of dried banana	90 THB/kg
Interest rate (i_{in})*	6.5%
Inflation rate (i_f)**	-0.9%
Life span of the system	10 years

*Data from the National Bank of Thailand (in 2020)
**Data from the National Bank of Thailand (in 2020)
***1 USD = 31.17 THB (4 May 2021)

4. Results and discussions

4.1. Performance of the dryer equipped with monitoring and control system

4.1.1. Thermal performance of the dryers

The results of the field experiment including the time variation of temperature, relative humidity, and the drying curves for each dryer are shown in the charts in Fig. 5.

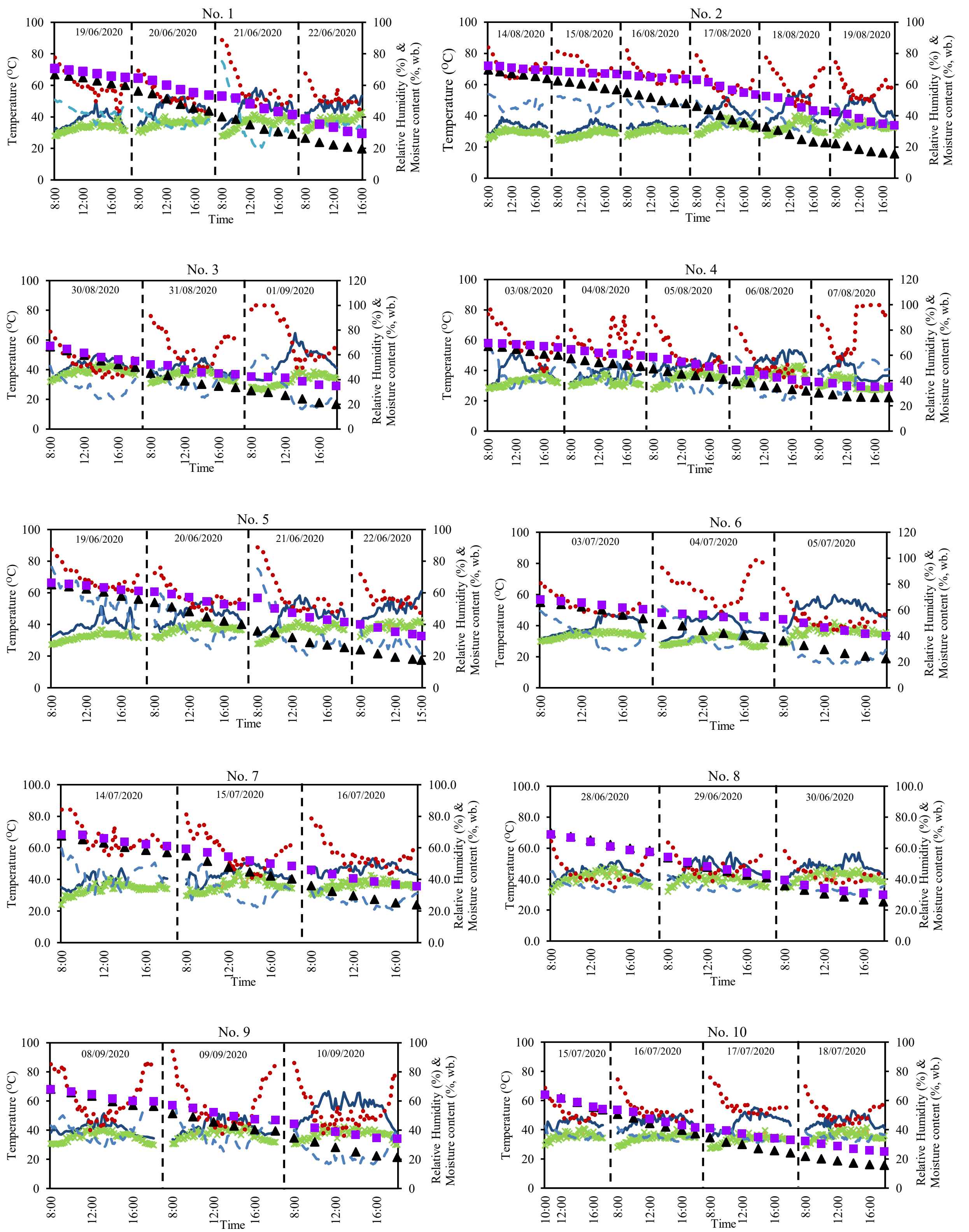

Fig.5 Time variation of air temperature inside the dryers ( ), ambient air temperature ( ), relative humidity of air inside the dryers ( ), relative humidity ambient air ( ), moisture content of banana inside the dryers (▲) and moisture content of banana dried with nature sun drying (■).

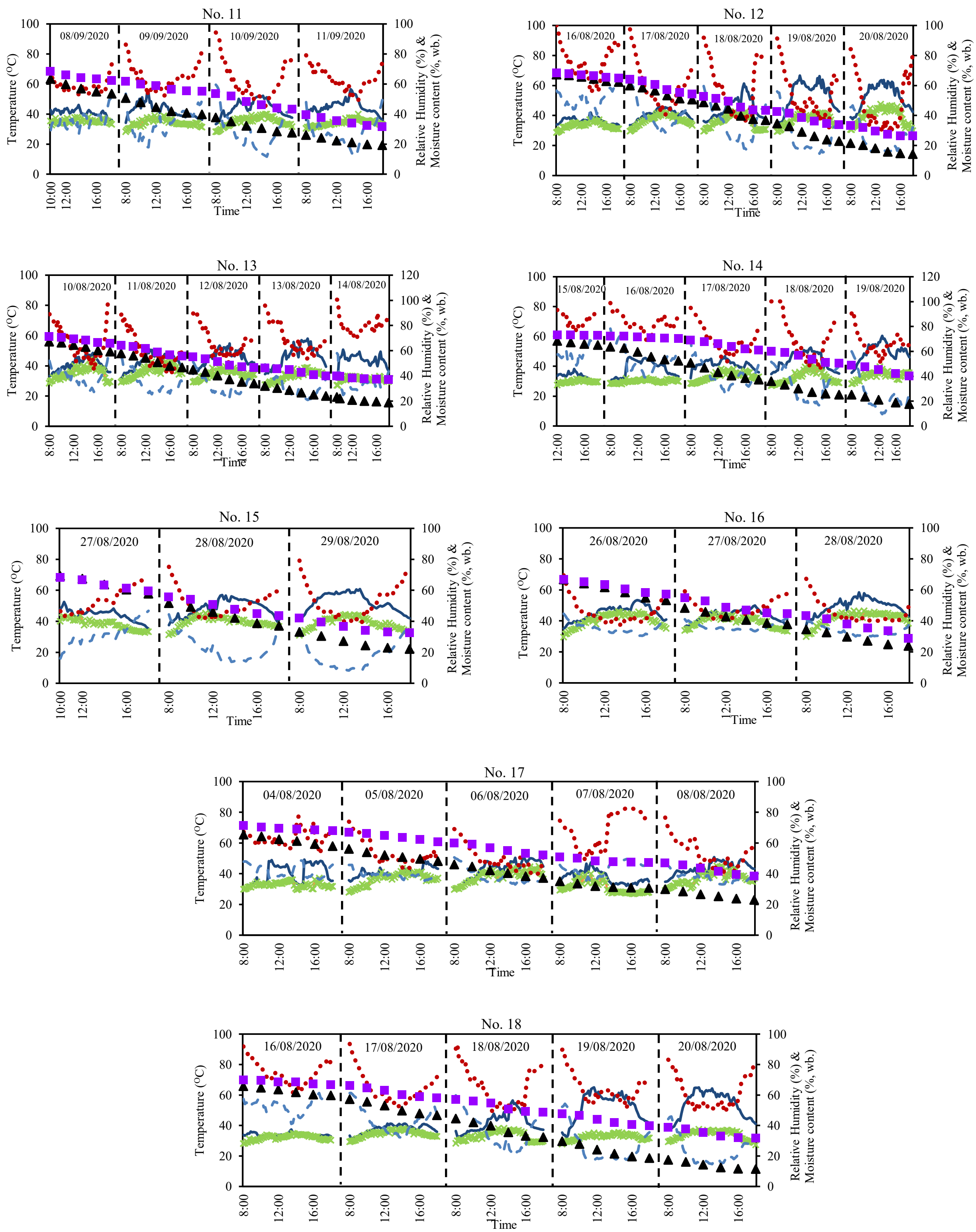

Fig.5 (Continue) Time variation of air temperature inside the dryers (▬▬), ambient air temperature (—×—), relative humidity of air inside the dryers (– – –), relative humidity ambient air (········), moisture content of banana inside the dryers (▲) and moisture content of banana dried with nature sun drying (■).

Solar radiation during most experiments fluctuated a lot due to the clouds, but the drying temperature was always higher than the ambient air temperature. This was because the air inside the dryers received thermal energy from both the environment inside the dryers and the greenhouse effect occurring inside the dryers. For all experiments, the relative humidity inside the dryers was lower than that of the ambient air. This was mainly due to the higher temperature of the drying air. As expected, the moisture content of bananas dried inside the dryers decreased more rapidly than that of the sample dried outside the dryer with the natural sun drying as shown by the drying curves.

As most existing solar dryers are small scale, it is difficult to compare the thermal performance of such dryers with that of the large-scale dryers which was the focus of this study. However, the performance of this type of dryers were comparable to the results of our previous work [11].

4.1.2. Performance of the monitoring and control system

The temperature and relative humidity data, and the images of the bananas being dried displayed by the mobile phone are shown in Fig.6. These results proved that the monitoring systems could collect and show the drying parameters via a mobile phone. For the control set-up, monitoring was done manually. Had the drying air temperature of the first day been lower than 40ºC, the dryer user could send a command via mobile phone to turn on the gas burner. On the other hand, had the drying air temperature been higher than 60ºC, the user could send a command via the phone to turn on the AC fans to reduce the temperature.

In summary, the study experimented and investigated the thermal performance of the dryers and the performance of the remotely controlled monitoring and control system. Based on the observation of the performance of each individual dryer, drying air temperature inside the dryers was always higher than ambient air while the relative humidity of the air inside the dryer was always lower than that of ambient air. The bananas inside the dryers dried faster than those outside the dryers. These proved the good thermal or heating performance of the dryers. The study also proved that the dryers can be remotely monitored to obtain drying data. Additionally, the gas burners and AC fans of the dryers can also be remotely controlled allowing for remote operation of the dryers via a mobile phone.

Fig. 6 Temperature and relative humidity data, and images of bananas in dryers 1-18 as displayed on the mobile phone.

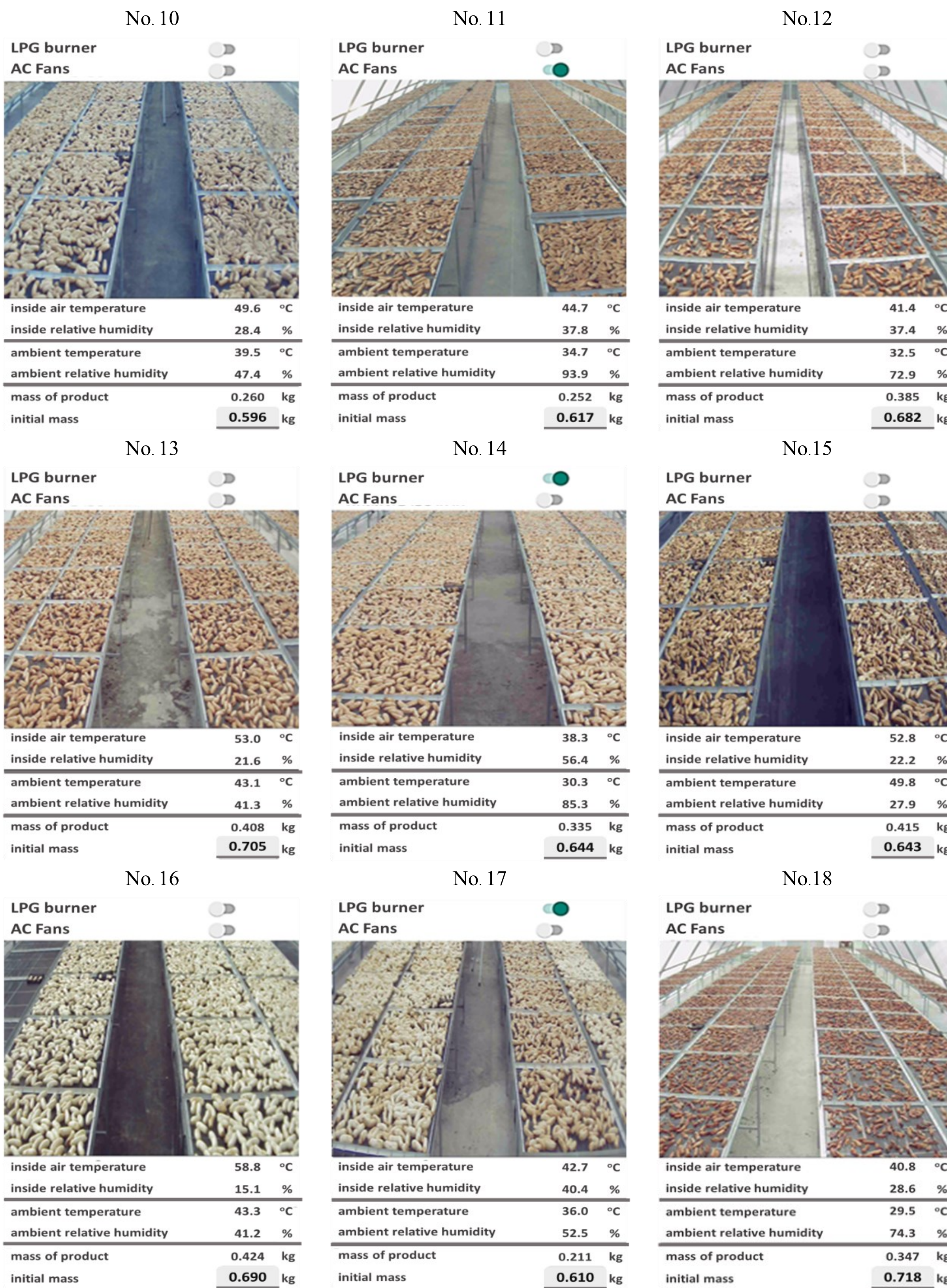

Fig. 6 (Continue) Temperature and relative humidity data, and images of bananas in dryers 1-18 as displayed on the mobile phone.

4.2. Water activity of dried bananas

The water activity (a_w) of dried bananas from the dryers are shown in Table 3.

Table 3 Water activity (a_w) of dried banana dried inside the dryer.

No. of the dryer	a_w
1	0.604
2	0.627
3	0.654
4	0.636
5	0.618
6	0.604
7	0.623
8	0.666
9	0.642
10	0.641
11	0.638
12	0.615
13	0.665
14	0.649
15	0.678
16	0.608
17	0.695
18	0.615

From Table 3, the range of water activity of the dried banana is 0.604-0.695. With this range, the dried bananas are safe from most micro-organisms [12].

4.3. Result of the economic analysis

The economic analysis showed a drying cost of 49 THB/kg, a payback period of 4.88 years and an internal rate of return of 16%. The payback period is relatively long. Thus, the Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy of Thailand set up a subsidy program for those who want to have this type of dryer. Under the subsidy program, dried banana producers can get a subsidy of 30% of the investment cost. With this support, the payback period becomes 2.77 years, which is more attractive to the dried banana producers.

5. Conclusions

Eighteen large-scale greenhouse type dryers equipped with the remotely operated monitoring and control systems were constructed for drying bananas in Phitsanulok province, Thailand. The field performance of these dryers was evaluated. The field experiments and investigations showed that the air temperature inside the dryers was always higher than the ambient air, while the relative humidity inside the dryer was always lower than that of the ambient air, thus reducing significantly drying time, compared to drying under ambient conditions. The remotely operated monitoring and control systems allow the dryer users to monitor the condition of the drying of the bananas via a mobile phone. An economic analysis of these dryers was then carried out, which showed that a drying cost of 49 THB/kg, a payback period of 4.88 years and an internal rate of return of 16%. However, with a 30% subsidy on investment cost from DEDE, the payback period can be reduced to a more acceptable period of 2.77 years.

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