THERMAL EFFICIENCY OF GREENHOUSE SOLAR DRYER FOR DRYING STICKY RICE (RD6) AND HEAT TRANSFER MODELING

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Abstract

This research presents the experimental performance of greenhouse solar dryers and heat transfer modeling of greenhouse solar dryers for drying sticky rice. Five batches of sticky rice were dried; for each batch, we used 5,000 kilograms of sticky rice. The parameters used in the heat transfer model are solar radiation, air temperature, relative humidity and airflow rate. The numerical solution was programmed in C^{++}. The results showed that the moisture content, Root mean square error ($RMSE$) and determination coefficient (R^2); $RMSE$ =0.4741 and R^2 =0.9859 respectively. The thermal efficiency of the greenhouse solar dryer was between 24.0%-27.0%.

Keywords: greenhouse solar dryer, sticky rice (rd6), heat transfer modeling, thermal efficiency

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Introduction

Thailand has rice varieties including Glutinous rice or Sticky rice and rice. The sticky rice with the most outstanding characteristics is Gorkhor 6 (RD 6). It is a new type of sticky rice. Caused by breeding by crossing breeds to combine genes. DNA markers are used for selection in conjunction with standard breeding (Rice Department, 2017).

Sticky rice is another type of rice widely grown in the northeastern region, including the area of Thung Kula Rong Hai. Most of them are grown for household consumption because people in this region like to consume sticky rice. Some of the remaining items will be sold. Alternatively, they farm sticky rice specifically for sale in some cases or provinces. Sticky rice is considered a local food of the people of the northeastern region (Agricultural Statistics of Thailand, 2023). In many countries, agricultural products are dried under the open sun. However, this way of drying degrades the quality of the dried products due to interference from external impurities and uneven drying rates. Numerous types of solar dryers have been designed and developed in various parts of the world, yielding varying degrees of technical performance, such as tunnel dryers, greenhouse solar dryers, hybrid dryers and mixed dryers. Drying is produced successfully even under unfavorable weather conditions. In the solar mode of operation, these are the most cost-effective types of dryers and are easy to fabricate and use. With this open sun method, substantial losses of sticky rice due to insects, animals and rain usually occur during drying. To overcome this problem, well-performed dryers are needed to dry sticky rice. In the tropics, Thailand receives abundant solar radiation (Janjai et al., 2005). Consequently, the use of solar dryers for sticky rice drying is reasonable, although several types of solar dryers have been developed in the last 50 years (Funholi et al., 2010; Janjai et al., 2007; Janjai et al., 2009; Murthy, 2009; Sharma et al., 2009; Piwsaoad (2016); Piwsaoad, 2019; Piwsaoad & Phusumpao, 2021). They could not meet the high demand for sticky rice drying.

As a result, our research group has developed the solar dryer to dry agricultural products. It was successfully used for drying fruits and vegetables. However, it has not been tested to dry sticky rice.

Therefore, the objectives of this research were to investigate the performance of the solar dryer for drying sticky rice (In this research, the performance of the greenhouse solar dryer is expressed by the thermal efficiency of the greenhouse solar dryer and the moisture content of the product.) and to develop heat transfer modeling to predict the moisture content of sticky rice (RD6).

Materials and Methods

1. Experimental setup

The greenhouse solar dryer was installed in Loei Province, Thailand. The dryer consists of a polycarbonate sheet on a concrete floor (The dimensions of the polycarbonate sheet are 1.22 m in width, 30.0 m in length and thickness is 0.6 mm.). The dimensions of the dryer are 9.0 m in width, 24.0 m in length and 4.0 m in height. To ventilate the dryer, nine DC fans operated by two 50-W solar cell modules were installed in the wall opposite the air inlet. The greenhouse solar dryer and measuring points, sticky rice inside the dryer, and sticky rice samples outside the dryer are shown in Figures 1, 2 and 3.

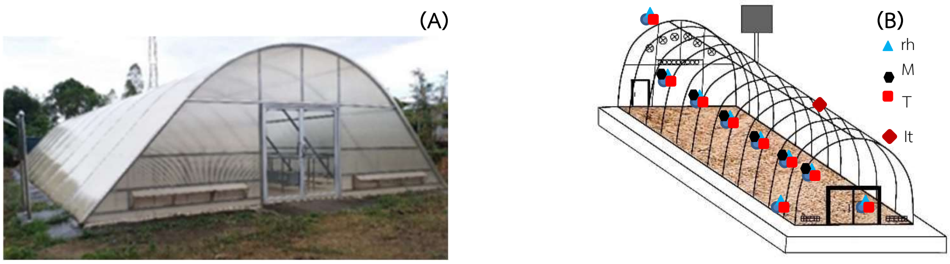

Figure 1 (A) The greenhouse solar dryer (B) The measuring points

Figure 2 Sticky rice inside the dryer

Figure 3 (A) Sticky rice samples inside the dryer
(B) Sticky rice samples outside the dryer

Solar radiation passes through the polycarbonate roof and heats the product in the dryer and the concrete floor, increasing the temperature of the dryer. Ambient air is drawn in through an air-inlet at the bottom of the front side of the dryer and is heated by the floor, and the products are exposed to solar radiation. Direct exposure to solar radiation and heated air enhances the drying rate of the products. Moist air passing through and over the products is sucked from the dryer by the fans at the top of the rear side of the dryer.

2. Experimental Procedure

In this study, sticky rice was dried inside the solar dryer to investigate the dryer potential (sticky rice 5000 kg; thickness 20 cm.). The drying of sticky rice will be studied. The quantity will be measured including solar radiation intensity, air temperature, air relative humidity, air flow rate, and moisture content of sticky rice. The data obtained from all measurements will be analyzed to determine how changes in various quantities affect the reduction of moisture content and then be used in the model in the next step.

The experimental runs were conducted from October 2023 to November 2023. Solar radiation was measured by a pyranometer (Kipp & Zonen model CMP 3) placed on the roof of the dryer. Thermocouples (K type) were used to measure air temperatures in the different positions of the dryer. A hot wire anemometer (Airflow, model TA5) was used to monitor the air speed at the inlet and outlet of the dryer. The relative humidity of ambient air and drying air were periodically measured by a hygrometer (Electronnik, model EE23). The measuring tools, measured quantity and accuracy are shown in Table 1.

Table 1 Measuring tools, Measured quantity and accuracy

Measuring tools	Measured quantity	accuracy
Pyranometer	Solar radiation	± 0.5%
Thermocouples	Air temperatures	± 2%
Hot wire anemometer	Airflow	± 2%
Hygrometer	Relative humidity	± 2%

Five batches of drying tests were carried out. For each batch, 5,000 kilograms of sticky rice were placed on the floor inside the dryer. Each day, the experiment started at 8:00 a.m. and lasted until 6:00 p.m. The drying was continued on subsequent days until the desired moisture content was reached. Product samples (2 kg) were placed at various positions inside and outside the dryer (open sundry). They were weighed periodically at two-hour intervals using a digital balance (Kern, model 474 – 42). At the end of the experimental drying, the exact dry solid weight of the product samples was determined by the oven method (103 °C for 24 hours). The moisture content during drying was estimated from the weight of the product samples and the estimated dried solid mass of the samples (Piwsaoad, 2019).

3. Heat transfer modeling

The heat transfer modeling consists of 5 equations 1) the energy balance of the cover, 2) the energy balance of the air inside the dryer, 3) the energy balance of the product, 4) the energy balance on the floor and 5) the mass balance equation. The details are as follows (Piwsaoad, 2016).

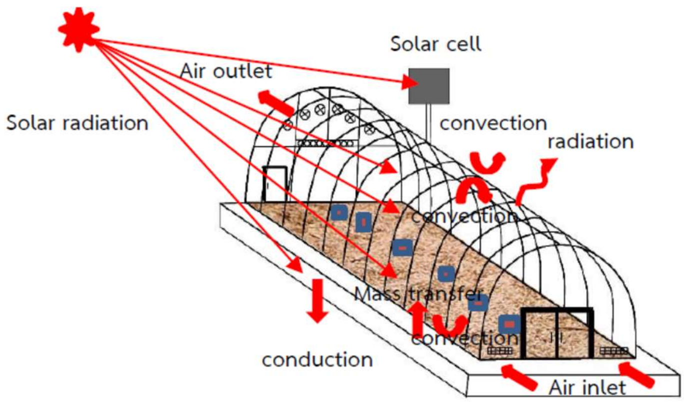

Figure 4 The schematic diagram of heat and mass transfer

3.1 Energy balance of the cover

The energy balance of the cover is considered the rate of accumulation of thermal energy in the cover, caused by various quantities that affect the cover according to the equation (1).

$$m_c c_{p,c}(\frac{dT_c}{dt}) = h_{c,c-a}\,(T_a - T_c)\,A_c + (h_{r,c-s}) \\ (T_s - T_C)A_c + (h_{w,c-amb}\,(T_{amb} - T_C)A_c \\ +(h_{r,a-p}(T_p - T_a) + (\alpha_c(T_c I_t A_c) \quad (1)$$

From equation (1); m_c is mass of the cover (kg), $C_{p,c}$ is specific heat of cover ($Jkg^{-1}K^{-1}$), T_C is the cover temperature (K), $h_{c,c-a}$ is convective heat transfer coefficient between the cover and the air in the greenhouse solar dryer ($Wm^{-2}K^{-1}$), T_a is the drying air temperature (K), A_c is the cover area (m^2), $h_{r,c-s}$ is radiative heat transfer coefficient between the cover and the sky ($Wm^{-2}K^{-1}$), T_s is the sky temperature (K), $h_{w,c-amb}$is convective heat transfer coefficient between the cover and ambient air due to wind ($Wm^{-2}K^{-1}$), T_{amb} is the ambient temperature (K), α_c is the absorptance of the cover (decimal), I_t is the solar radiation (Wm^{-2}).

3.2 Energy balance of the air inside the dryer

This energy balance is the rate of accumulation of thermal energy in the air inside the dryer according to the equation (2).

$$m_p c_p(\frac{dT_a}{dt}) = A_p h_{c,p-a}\,(T_f - T_a) + A_p h_{c,p-a}\,(T_p - T_a) \\ +D_p A_p m_c c_p \alpha_p\big(T_p - T_a\big)\frac{dM_p}{dt} \\ +(\rho_a v_a c_{p,c} T_a - \rho_a v_{in} c_{p,a} T_{in}) \\ +U_c A_c(T_a - T_a) + [(1 - F_p)(1 - \alpha_f) \\ +(1 - \alpha_p)F_p] I_t A_c \tau_c \quad (2)$$

From equation (2); m_p is mass of the product (kg), C_p is specific heat of air in the product ($Jkg^{-1}\,K^{-1}$), A_p is product area (m^2), $h_{c,p-a}$ is convective heat transfer coefficient between the product and the drying air ($Wm^{-2}K^{-1}$), T_f is temperature of the floor (K), D_p is the average distance between the cover and the product (m), α_p is the absorptance of the product (decimal), T_p is temperature of the product (K), M_p is the moisture content of product in the dryer model (db, decimal), $\alpha_a$is density of air (kgm^{-3}), V_{out} is outlet air flow rate (m^3s^{-1}), C_{p-a} is specific heat of air in the product ($Jkg^{-1}K^{-1}$), $T_{out}$is temperature of the air at the outlet of the dryer (K), V_{in} is inlet air flow rate (m^3s^-

^{1}), T_{in} is temperature of the air at the inlet air of the dryer (K), U_c is overall heat loss coefficient from the cover to ambient air (Wm^{-2}K^{-1}), F_p is fraction of solar radiation falling on the product (decimal), α_f is absorptance of the floor (decimal), τ_c is transmittance of the cover (decimal).

3.3 Energy balance of the product

Rate of accumulation of thermal energy in the product according to the equation (3)

$$m_c(c_{pg} + c_{pl}M_p)\frac{dT_p}{dt} = A_p(h_{c,p-a}(T_a - T_C) + A_p h_{r,p-c}(T_c - T_p) + D_p A_p \rho_p L_p + c_{pv}(T_a - T_p)\frac{dM_p}{dt} + F_p \alpha_p I_t A_c \tau_c \quad (3)$$

From equation (3); m_p is mass of product (kg), C_{pg} is the specific heat of air in the dryer (Jkg^{-1}K^{-1}), C_{pl} is the specific heat of liquid in the product (Jkg^{-1}K^{-1}), ρ_p is density of product (kgm^{-3}), L_p is the latent heat of evaporation of the product (Jkg^{-1}K^{-1}).

3.4 Energy balance on the floor

Rate of accumulation of thermal energy in the floor according to the equation (4).

$$m_f c_{p,f}(\frac{dT_f}{dt}) = A_f h_{c,f-a}(T_a - T_f) + A_f h_{D,f-un}(T_{un} - T_f) + (1 - F_p)\alpha_f I_t A_f \tau_c \quad (4)$$

From equation (4) $m_f$is mass of floor (kg), $h_{D,f-u}$ is conductive heat transfer between the floor and the underground $(\mathrm{Wm^{-2}K^{-1}})$, C_{pf} is specific heat of floor $(\mathrm{Jkg^{-1}K^{-1}})$, T_{un} is ground temperature (K).

3.5 Mass balance equation

The accumulation rate of moisture in the air inside dryer according to the equation (5).

$$\rho_a v\frac{dH}{dt} = A_{in}\rho_a H_{in} v_{in} - A_{out}\rho_a H_{out} v_{out} + D_p A_p \rho_{d,p}\frac{dH}{dt} \quad (5)$$

From equation; (5) v is speed of the air (ms^{-1}), A_{in} is total cross-sectional area of the air inlets (m^{2}), A_{out} is total cross-sectional area of the air outlets (m^{2}), H is humidity ratio (kgkg^{-1}), H_{in} is humidity ratio of air entering the dryer (kgkg^{-1}), H_{out} is humidity ratio of the air leaving the dryer (kgkg^{-1}) and $\rho_{d,P}$ is density of the dried product (kgm^{-3}).

3.6 Solution procedure

The system of equations (1to5) is solved numerically using the finite difference technique. On the basis of the drying air temperature and relative humidity inside the dryer. This system of equations is a set of implicit calculations for the time interval Δt. These are solved by the Gauss-Jordan elimination method using the recorded values for the drying air temperature and relative humidity, the change in moisture content of the product (ΔM) for the given time interval. The numerical solution was programmed as shown in Figure 5.

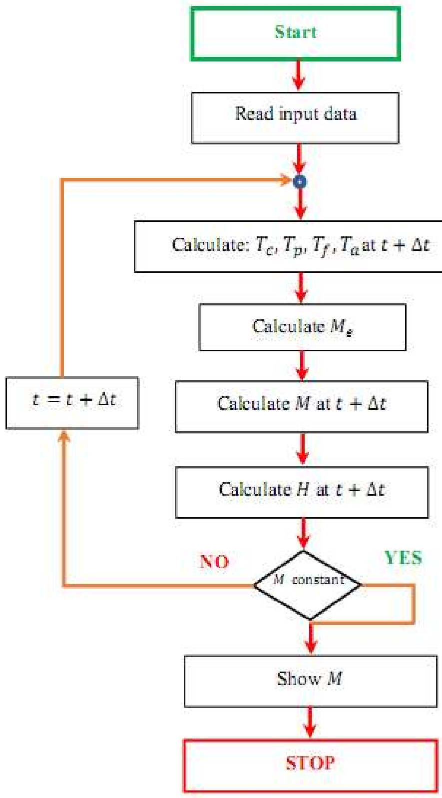

Figure 5 The numerical solution programmed

The process is repeated until the final time is reached. The numerical solution was programmed in Compaq Visual FORTRAN. Three statistical parameters were used for performance analysis. Root means square error $RMSE$ and determination coefficient $R^2$of agreement were computed to estimate the overall model performance.

3.7 Performance analysis

Statistical parameters were used for performance analysis. Root mean square error $(RMSE)$ and determination coefficient (R^2) of agreement were computed to estimate the overall model performance. These are defined as:

$$R^2 = \frac{1-R\,esidual\ sum\ of\ squares}{Corrected\ total\ of\ squares} \tag{6}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{pre,i}-MR_{mea,i})^2}{n}}. \tag{7}$$

Where $M_{pre,i}$ is the predicted moisture contents; $M_{mea,i}$ is the measured moisture contents; $i = 1 - N; N$ is the number of observations; $RMSE$ and R^2 are the two most commonly used statistical parameters, which represent the degree of explanation and the average difference between estimated and observed values. Values of R^2 close to 1 with small values for the error terms are desirable (Piwsaoad & Phusumpao, 2021).

4. The thermal efficiency of the solar dryer

The thermal efficiency was calculated from the drying rate to the energy yield rate for sticky rice drying is determined by:

$$\eta_{solar} = \frac{\dot{m}_w h_{fg}}{A_{solar} I_t} \times 100\ (\%) \tag{8}$$

Where η_{solar} is the thermal efficiency (%); $\dot{m}_w$ is the evaporation rate of water (kg/s); h_{fg} is the latent heat of vaporization of water (kJ/kg); I_t is the total radiation incident on the dryer (kW/m^2); A_{solar} is the solar radiation area of the dryer (m^2).

Result

1. Experimental results

Drying experiments of sticky rice in the greenhouse solar dryer were carried out from October 2023 to November 2023. The comparison of air temperature at six different locations inside the dryer and the ambient air temperature was used for the experimental runs of solar drying of sticky rice.

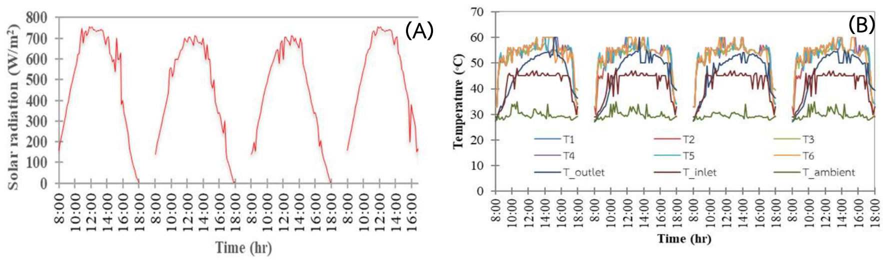

Figure 6 (A) Variation of solar radiation with time of the day during the drying
(B) Variation of temperature at different positions during the drying

Solar radiation from Figure 6 (A) shows that the solar radiation does not fluctuate due to the clear sky. The variation of solar radiation with time of the day during the drying of sticky rice varied from 150 – 750 (W/m^2).

In Figure 6 (B), the patterns of temperature change in different positions were comparable for all positions. The variation of ambient temperature and the temperature at different positions inside the solar dryer during the drying of sticky rice varied from 23 - 65 (°C).

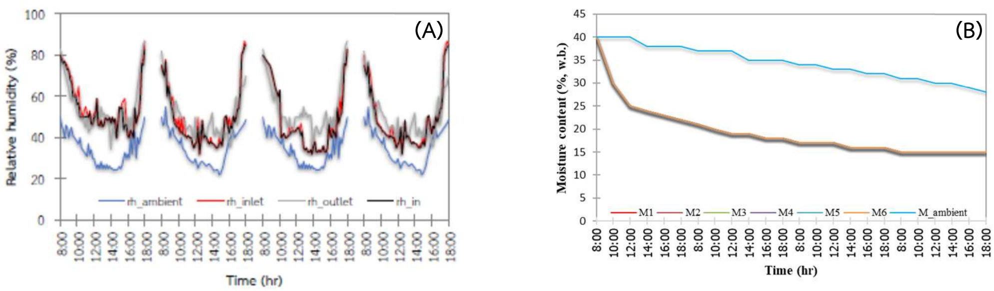

Figure 7 (A) Variation of relative humidity with time of the day during the drying
(B) moisture content of sticky rice during the drying

In Figure 7 (A), relative humidity decreased over time at different positions inside the dryer during the first half of the day while the opposite is true for the other half of the day. The variation of relative humidity with time of the day during the drying of sticky rice varied from 22.0 – 87.0 (%).

In Figure 7 (B), the comparison of moisture content at different positions inside the dryer and the open sun drying for the experimental runs of solar drying of sticky rice. The moisture contents of sticky rice inside the solar dryer were reduced from an initial value of 40.0% (w.b.) to a final value of 15.0% (w.b.) within four days. In contrast, the moisture contents of the open sun-dried samples were reduced to 25.0% (w.b.) in the same period.

2. The thermal efficiency of the greenhouse solar drye

The thermal efficiency of the greenhouse solar dryer of sticky rice is shown in Figure 8.

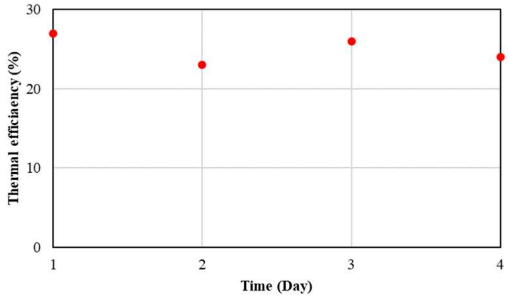

Figure 8 Thermal efficiency of the solar dryer

The thermal efficiency of the solar dryer for sticky rice drying, calculated per day, was found to be between 24.0-27.0%.

From Figures 6-8, it is found that the intensity of solar radiation, Air temperature, relative humidity of air, air flow rate and the moisture content of sticky rice obtained from drying with a greenhouse solar dryer was similar to Kanasri et al., (2017) and Wongbubpa & Chitsomboon, (2022).

3. Modeling results

In this work, the researcher designed the following: 1) The floor of the dryer by letting the edge of the dryer floor on every side up 10 centimeters to prevent water from entering and retaining the heat, 2) Adjust the air inlet to be smaller so that the airflow rate decreases, resulting in higher heat inside the dryer.

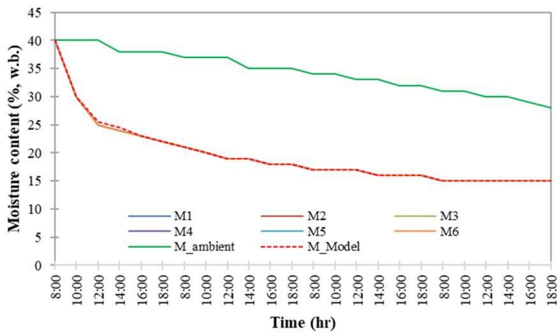

Figure 9 The simulated moisture content

In Figure 9, the model predicts well the variation of the moisture content during the drying. Comparison of the simulated moisture content are 0.4741 and 0.9859 respectively.

Discussions

Solar radiation passes through the polycarbonate roof and heats the product in the dryer and the concrete floor. Temperatures in different positions varied within a narrow band. In addition, temperatures at each position differed significantly from the ambient air temperature. Relative humidity decreased over time at different positions inside the dryer during the first half of the day, while the opposite is true for the other half of the day. No significant difference was found between relative humidity of different positions inside the dryer. However, relative humidity was significantly different for all positions inside the dryer compared to the ambient air. The relative humidity of the air inside the dryer was lower than that of the ambient air. The moisture content of sticky rice gradually decreased. From the moisture content decreasing curves of sticky rice at different positions, there was a difference equal to 2.0% (w.b.); when compared with research using other types of dryers, it was found that they had similar characteristics (Suchart et al., 2012; Wongbubpa & Chitsomboon, 2022). After drying, the moisture content of the paddy is 14% (w.b.).

In the last period, the moisture content was almost the same. It indicates that the moisture content drying rate of sticky rice at different positions is quite uniform. Compared to open sun-dried, the moisture content value decreases more slowly.

Thermal efficiency of a greenhouse solar dryer for drying sticky rice. Which is calculated per day is between 24.0-27.0%, with a difference equal to 3.0%.

A system of equations for heat and mass transfer has been developed for drying sticky rice in a greenhouse solar dryer. The simulated air temperatures inside the dryer reasonably agreed with the observed temperature data. Reasonable agreement was found between the experimental and simulated moisture contents of sticky rice during the drying and the accuracy was within the acceptable range. This model can be used to provide design data for the greenhouse solar dryer and optimize this type of solar dryer.

Conclusions

Five sets of sticky rice were collected, and the drying air temperature varied from 23°C to 65°C during the drying. This drier can be used to add 5,000 kilograms of sticky rice. The sticky rice dried inside the greenhouse solar dryer was completely protected from rain, insects and dust. The dried sticky rice was a high-quality product. The performance of the solar dryer for drying sticky rice has been experimentally investigated. It was found that using this dryer led to a considerable reduction in drying time compared to that of open sun drying. The moisture content of sticky rice inside the solar dryer was reduced from an initial value of 40.0% (w.b.) to a final value of 15.0% (w.b.) within four days whereas the moisture content of the open sun-dried samples was reduced to 25.0% (w.b.) in the same period.

The thermal efficiency of the greenhouse solar dryer for sticky rice drying was tested for four days. It was found that day 1and3 was efficient, and days 2-4 decreased efficiency depending on solar radiation intensity.

The heat transfer model of the greenhouse solar dryer showed values of $RMSE = 0.4741$ and $(R^2) = 0.985$, meaning that the experimental results and predictions were consistent.

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