Study on effectiveness of continuous solar dryer integrated with desiccant thermal storage for drying cocoa beans

著者	DINA Sari Farah, AMBARITA Himsar, NAPITUPULU Farel H, KAWAI HIDEKI
journal or publication title	Case Studies in Thermal Engineering
volume	5
page range	32-40
year	2015-03
URL	http://hdl.handle.net/10258/00009211

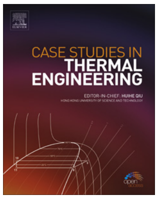
doi: info:doi:10.1016/j.csite.2014.11.003

Case Studies in Thermal Engineering 5 (2015) 32–40

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite



Study on effectiveness of continuous solar dryer integrated with desiccant thermal storage for drying cocoa beans

Sari Farah Dina [a,b], Himsar Ambarita [b,*], Farel H. Napitupulu [b], Hideki Kawai [c]

[a] Research and Standardisation Bureau Medan, Jl. Sisingamangaraja No. 24, Medan 20217, Indonesia
[b] Mechanical Engineering, University of Sumatera Utara, Jl. Almamater, Medan 20155, Indonesia
[c] Department of Mechanical Systems of Engineering, Muroran Institute of Technology, 27-1 Mizumoto-cho, Muroran 050-8585, Japan

ARTICLE INFO

Article history:
Received 24 October 2014
Accepted 21 November 2014
Available online 2 December 2014

Keywords:
Cocoa
Solar
Thermal storage
Desiccant

ABSTRACT

The main objective is to assess effectiveness of continuous solar dryer integrated with desiccant thermal storage for drying cocoa beans. Two type of desiccants were tested, molecular sieve 13× ($Na86\ [(AlO_2)86\cdot(SiO_2)106]\cdot264H_2O$) as an adsorbent type and $CaCl_2$ as an absorbent type. The results revealed that during sunshine hours, the maximum temperature within the drying chamber varied from 40 °C to 54 °C. In average, it was 9–12 °C higher than ambient temperature. These temperatures are very suitable for drying cocoa beans. During off-sunshine hours, humidity of air inside the drying chamber was lower than ambient because of the desiccant thermal storage. Drying times for intermittent directs sun drying, solar dryer integrated with adsorbent, and solar dryer integrated with absorbent were 55 h, 41 h, and 30 h, respectively. Specific energy consumptions for direct sun drying, solar dryer integrated with adsorbent, and solar dryer integrated with absorber were 60.4 MJ/kg moist, 18.94 MJ/kg moist, and 13.29 MJ/kg moist, respectively. The main conclusion can be drawn here is that a solar dryer integrated with desiccant thermal storage makes drying using solar energy more effective in term of drying time and specific energy consumption.

1. Introduction

Cocoa beans (*Theobroma cacao*) are one of the leading commodities of Indonesian plantation, along with rubber and crude palm oil. In 2011–2012, Indonesia produced 440 Mt of cacao beans. This makes Indonesia one of the biggest cacao beans producers after Ivory Coast and Ghana [1]. Smallholder farmers produce almost 95% of Indonesian cocoa beans. Since the postharvest is processed traditionally, the Indonesian cacao bean is known with poor quality production. This is the main drawback of Indonesian cocoa beans and it can lower the price in international market. In order to overcome the weakness, the Government of Indonesia has been releasing a national movement on improvement of production and quality of cocoa beans since 2009.

Fermentation and drying are two main steps in the postharvest processing of cocoa beans. These steps play an important role in the formation of flavor and taste. These steps should be treated properly in order to improve the quality of cocoa beans. The main objective of drying is to reduce the moisture content of cocoa beans to moisture content less than 10%.

---

[*] Corresponding author.
E-mail address: himsar@usu.ac.id (H. Ambarita).

http://dx.doi.org/10.1016/j.csite.2014.11.003
2214-157X/

However, drying method can improve the quality of dried cocoa beans. Many researchers have reported study on the effects of drying method to the cocoa beans quality. Jinap et al. [2] studied several different types of drying conditions evaluating the acidity and volatile fatty acids and concluded that cocoa beans dried in an oven at 60 °C retain a high content of acetic, propionic, butyric, isobutyric, and isovaleric acids, which helps in the making of a low quality chocolate. Camu et al. [3] showed that during drying of cocoa beans, strong browning reactions occur that include oxidation of pholyphenols with reduction of astringent and bitter taste. When the drying is slow, non-volatile lactic acid may partly be transported by the water from the bean to the husk. Polyphenols and polyphenols oxidase are sensitive to the drying process. Bonaparte et al. [4] have reported a study on field comparison of solar drying and open-air sun-drying cocoa beans. The results showed that the cocoa beans from indirect dryer showed the highest quality and those from the direct sun drying the poorest. Hii et al. [5] carried out a study to compare the quality characteristics of cocoa beans dried using solar dryer (indirect type) and sun dryer (direct type) with perforated and non-perforated platforms. Results showed that solar drying can be used as an alternative to sun drying with a better quality.

Many designs of solar dryer for drying agricultural products can be found in literature [6]. The good design of solar dryer can result in a hot drying air in order of 10–25 °C above the ambient temperature. However, solar dryer which uses solar energy as energy resource has two main weaknesses. It is intermittent by its nature and is dependent on the the weather conditions of the location. In the nighttime, when the sunshine is off, ambient temperature decreases, while the relative humidity increases. In some cases, the dried object will re-absorb the moisture. This will make the drying time longer and the worst case, it can ruin the dried object because of mold [7]. To avoid or to reduce the intermittent effects, some researchers proposed solar dryer integrated with a thermal energy storage material to store excess heat in the daytime and uses it in the nightime [8].

The excess thermal energy can be stored in well-insulated fluids or solid in internal energy of material as sensible heat, latent heat and thermo-chemical or combination of these [9]. Some researchers have reported their study on the thermal storage material for drying foods and agricultural products. Buttler and Troeger [10] have experimentally evaluated a solar collector-cum-rockbed storage system for peanut drying. Devahastin and Pitaksuriyarat [11] investigated the feasibility of using latent heat storage with paraffin wax as a phase change material to store excess solar energy during drying and release it when the energy availability is inadequate or not available. The effect on drying kinetics of a food products (sweet potato) was explored. Shanmugam and Natarajan [12] have reported study on the performance of an indirect forced convection and desiccant integrated solar dryer for drying of green peas and pineapple slices. The system is operated in two modes, sunshine hours and off-sunshine hours.

The aforementioned studies showed that, solar dryer is the best method for drying cocoa beans in comparison with conventional direct sun drying and artificial drying. However, its intermittent is the main weakness. Thermal energy storage can be used to avoid the intermittent effect. To the best knowledge of the authors, study on drying cocoa beans using a solar dryer integrated with thermal energy storage has not been reported. This paper deals with solar dryer integrated with thermal energy storage for drying of cocoa beans. The main objective is to study the effectiveness of continuous solar dryer integrated with thermal energy storage in term of drying time and specific energy consumption. The results are expected to provide the necessary informations in order to support the Government of Indonesia movement on improving the quality of Indonesian cacao.

2. Materials and methods

2.1. Sample preparation

Cocoa fruits were collected from Deli Serdang regency of Sumatera Utara province of Indonesia. Before drying, the fresh cocoa beans were fermented using boxes made of Styrofoam for five days. The fermentation methods have been reported elsewhere [13]. The cocoa beans for one batch of drying was 1 kg with initial moist content varies from 59.15% to 60.37%. This is a typical initial moist content for fermented cocoa beans in Indonesia.

2.2. Solar dryer and drying method

A prototype solar dryer has been fabricated and used in experiments. The solar dryer is shown in Fig. 1(a). It consists of three main components: drying chamber; solar collector; and thermal energy storage. The drying chamber is a room with dimension of 50 cm × 50 cm × 50 cm. The dried cocoa beans were spread in a drying tray made of perforated aluminum sheet with an area of 49 cm × 49 cm. Thermal storage was placed in an open container made of steel with dimension of 30 cm × 30 cm × 5 cm. Picture of the drying tray, cocoa beans and the thermal storage are shown in Fig. 1(b). The solar collector is a flat plate type with dimension of 2 m × 0.5 m × 0.1 m. The absorber was black-painted made of 1 mm galvanized steel sheet. Two plain window glasses separated by a 2 cm air gap were used as transparent covers to prevent the heat loss from the top. The solar collector was oriented Northward with a tilt angle of 60°. Fig. 1(c) shows detailed cross section and thermal resistant analogy of the solar collector envelope.

As a note, drying is a simultaneous heat and mass transfer process and is followed by evaporation. The drying process can be driven by temperature difference and/or concentration difference. A lower vapor concentration of drying air above the surface can provide drying process, even though the temperature of the object is relatively low. In order to make drying process occur even if the temperature is low, the thermal storage material proposed in this study was desiccant and it can be recycled using heat from solar energy. The desiccant will be categorized as thermo-chemical energy storage. Two type of desiccant, $CaCl_2$ and molecular sieve 13× ($Na86\,[(AlO_2)86 \cdot (SiO_2)106] \cdot 264H_2O$), were tested. Based on the working mechanism, each desiccant will be categorized differently, $CaCl_2$ as absorbent type and molecular sieve 13× as adsorbent type.

The solar dryer was operated in two drying modes, daytime and nighttime. In the daytime, the cocoa beans is dried inside the drying chamber by using hot air resulted by the solar collector. In the same time, the thermal storage is heated using direct solar energy in order to store the heat and to release the

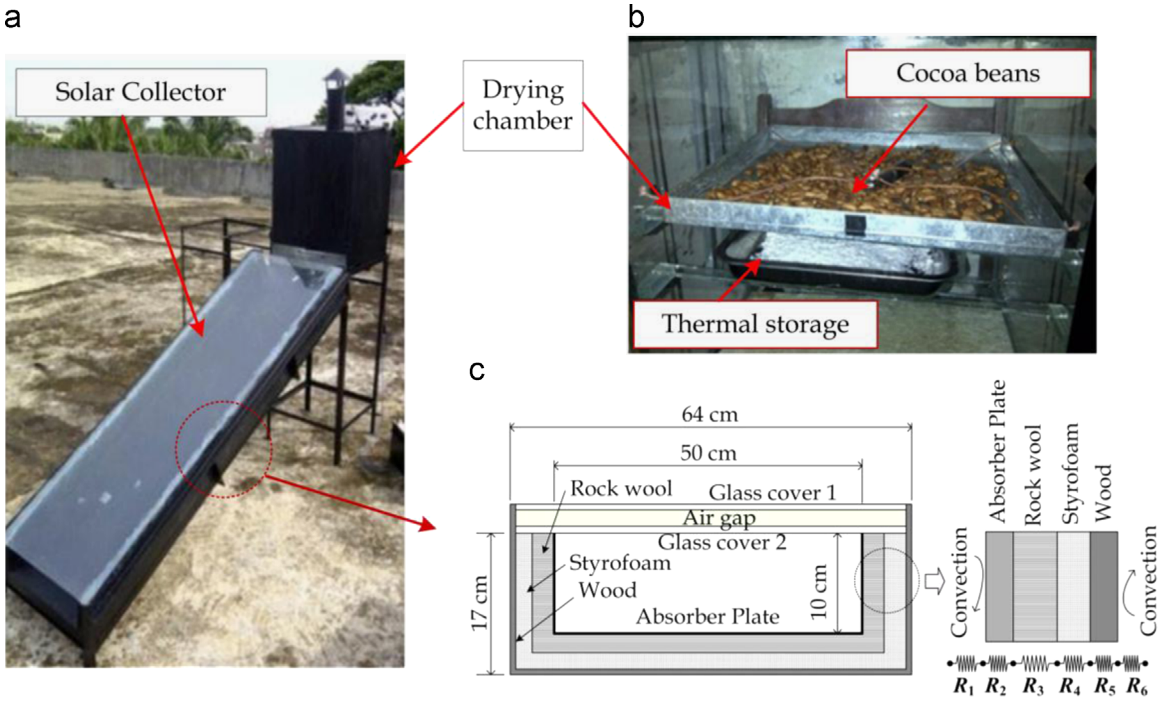


Fig. 1. Picture of the (a) experimental solar dryer, (b) drying tray, and (c) thermal resistance analogy of solar collector envelope.

moist. In the nighttime, the thermal storage is placed inside the drying chamber along with cocoa beans and the drying chamber was isolated from the ambient air. Thus, the drying process will be continued, even though temperature is relatively low. The meaning of continuous term here is that during sunshine hours and off-sunshine hours the drying process is uninterrupted.

In all experiments, temperatures, mass of the cocoa beans, relative humidity, wind velocity, and solar radiation were recorded every minute. Thermocouples of J type with an accuracy of 0.4% were used to measure temperatures. An Agilent 3497A data acquisition system with a 20 channel multiplexer was used to record measurements. To measure the humidity inside the drying chamber, 2 USB Temperature Humidity Logger were used. The accuracies of temperature and relative humidity were $\pm 0.5\,^{\circ}$C and $\pm 3\%$ RH, respectively. The mass of the cocoa beans was measured using a load cell weight system data logger with an accuracy of 0.01 kg. The desiccant mass was measured using an analytic balance (Mettler Toledo, USA) with capacity of 600 g and accuracy of 0.01 g. A HOBO micro station data logger was used to measure the weather conditions. They are ambient temperature, RH, solar radiation, and wind velocity. The schematic of the solar dryer and data measurement systems are shown in Fig. 2.

2.3. *Drying effectiveness*

As a note, the main objective of installing the thermal storage is to reduce drying time. The drying time is defined as the total time needed from the beginning until the equilibrium is reached. Thus, effectiveness of the solar dryer integrated with thermal storage will be assessed in terms of drying time and specific energy consumption.

The specific energy consumption (*SEC*) is defined as total energy received during drying divided by amount of water evaporated from the object:

$$SEC = \frac{Q_{net}}{m_{eva}} \tag{1}$$

where Q_{net} [kJ] and m_{eva} [kg water] are total energy received and mass of water evaporated from the cocoa beans, respectively. The total energy received during the drying is defined as the sum of energy radiation during sunshine hours and thermo-chemical energy released by desiccant during off-sunshine hours.

The received energy in the sunshine hours ($\dot{Q}_r$) was calculated as energy radiation absorbed in the solar collector minus heat loses from the collector:

$$\dot{Q}_r = F'(IA\tau\alpha) - \dot{Q}_l \tag{2}$$

where F' is the factor efficiency of the collector that is assumed 0.9 and I, A, τ, α are solar intensity [W/m^2], solar collector area [m^2], transmittance, and absorption coefficient, respectively. The total heat loses from the collector ($\dot{Q}_l$) is calculated by the following equation:

$$\dot{Q}_l = \dot{Q}_w + \dot{Q}_b + \dot{Q}_t \tag{3}$$

where $\dot{Q}_w$ [W], $\dot{Q}_b$ [W], and $\dot{Q}_t$ [W] are the heat loses from the wall, bottom, and the top of the solar collector, respectively. The heat loss from the wall and the bottom of the collector are calculated using the following equations, respectively:

$$\dot{Q}_w = U_w A_w (T_p - T_\infty) \tag{4}$$

$$\dot{Q}_b = U_b A_b (T_p - T_\infty) \tag{5}$$

Here U_w [W/m^2 K] and U_b [W/m^2 K] are overall heat transfer coefficient of wall and bottom of the solar collector, respectively. They are calculated using the thermal resistant analogy as depicted in Fig. 1(c). While, the heat loses from the top of the collector is determined using the following equation:

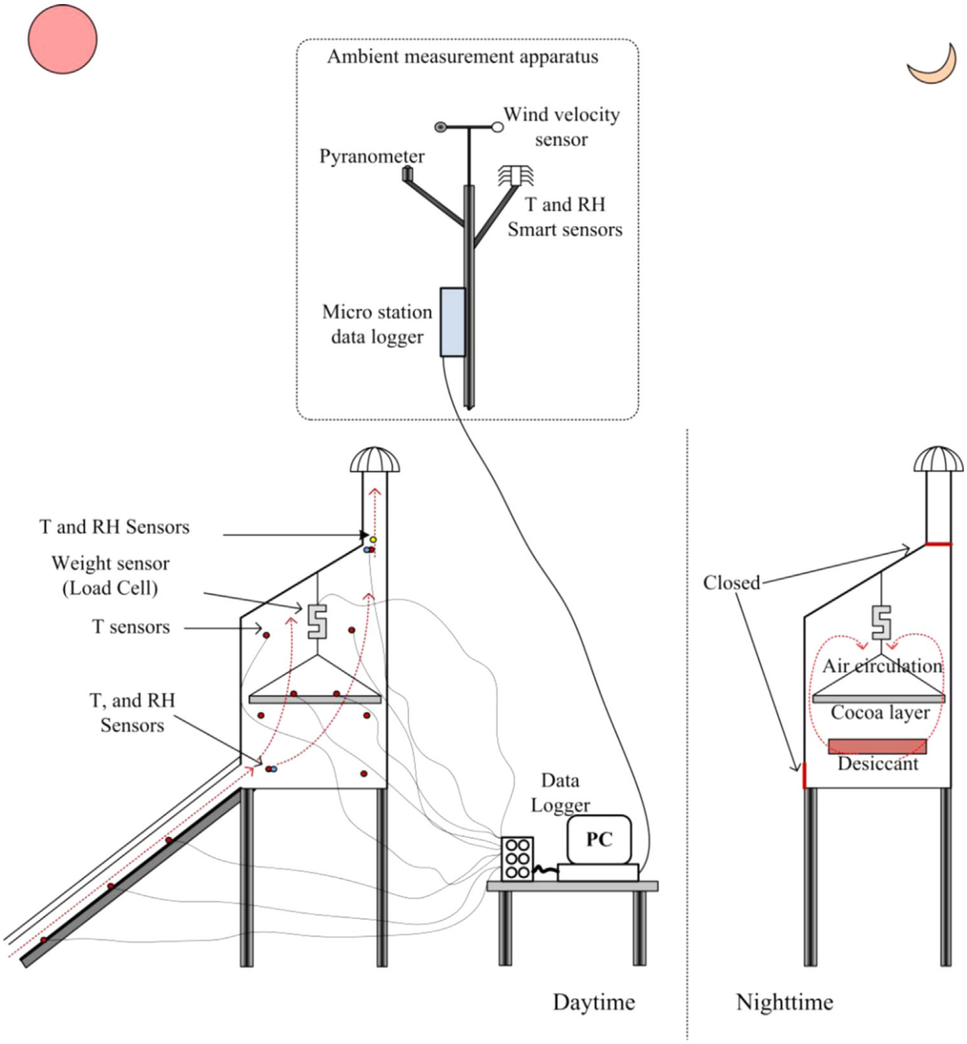


Fig. 2. Schematic of the solar dryer and measurement systems.

$$\dot{Q}_t = U_t A_t (T_p - T_\infty) \tag{6}$$

where U_t [W/m^2 K] is overall heat transfer coefficient from the top of the double glasses cover.

The thermo-chemical energy released by desiccant (Q_d) during the off-sunshine hours is calculated by

$$Q_d = m_d \Delta H_r \tag{7}$$

where m_d [kg] is mass of the desiccant and ΔH_r [kJ/kg] is enthalpy difference of the desiccant before and after off-sunshine drying. Using Eqs. (2) and (7), the specific energy consumption can be calculated by using the following equation:

$$SEC = \frac{Q_r + Q_d}{m_{eva}}. \tag{8}$$

2.4. Drying characteristics

Drying characteristics of the cocoa beans will be discussed in the form of moist content versus time curve. Non-dimensional moisture content (MR) was used and defined as

$$MR = \frac{M - M_e}{M_i - M_e} \tag{9}$$

where M, M_e, and M_i are moisture content at t time, moisture content at equilibrium, and moisture content at initial condition, respectively.

In this study, the cocoa bean is assumed as a sphere with radius of r [m]. The local moisture content (M) can be written as the following governing equation:

$$\frac{\partial M}{\partial t} = D_{eff} \frac{\partial^2 M}{\partial r^2} + \frac{2}{r} \frac{\partial M}{\partial r} \tag{10}$$

where D_{eff} [m^2/s] is an effective diffusivity. This parameter is a coefficient for mass transfer of the water within the object. The phase of water includes liquid and vapor. By using appropriate initial value and boundary conditions the analytical solution for Eq. (10) for a sphere object is [14–16]:

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[-D_{eff} n^2 \pi^2 t / r^2\right] \tag{11}$$

For a long drying time, the parameter n can be assumed as one. Thus, Eq. (11) can be linearized as

$$\ln MR = \ln \frac{6}{\pi^2} - \frac{\pi^2 D_{eff} t}{r^2} \tag{12}$$

By plotting ln MR versus time, the slope of the line will be the constant of the above linear equation. Thus, the effective diffusivity can be calculated using the following equation:

$$D_{eff} = slope \times \frac{r^2}{\pi^2}. \tag{13}$$

3. Results and discussions

Drying experiments had been carried out during April–June 2013 at a place in Medan city, Indonesia with geographic coordinate 3°34′ North and 98°40′ East. The drying experiments were divided into three groups. The first group is continuous solar drying integrated with adsorbent (molecular sieve), the second group is continuous solar drying integrated with absorbent ($CaCl_2$), and the third group is intermittent direct sun drying. Every drying mode were tested triplet, in other words nine batches of fermented cocoa beans were tested. The daytime of drying starts from about 9.00 am and finish at 5.00 pm and the nighttime starts at 5.00 pm and finish at about 9.00 am. The drying process is terminated if the equilibrium is reached. The results for each groups are presented in the below sections.

3.1. *Drying conditions*

In this section, drying conditions for continuous solar drying will be presented. The drying parameters such as temperature and humidity in the drying chamber and ambient air, solar radiation, and moisture ratio history of the cocoa beans will be discussed.

3.1.1. *Continuous solar drying with adsorbent*

In general, the drying process spent two daytimes and two nighttimes or total drying time was about 40 h. Typical drying conditions during experiments are shown in Fig. 3.

Fig. 3(a) shows temperatures history inside the drying chamber and ambient, also solar radiation in the first daytime. It can be seen that by noontime, solar radiation increases as time increases and in afternoon solar radiation decreases over time. In some certain minutes the incoming solar radiation decreases because of cloud. The minimum, maximum, and average solar radiations were 110.6 W/m^2, 969.4 W/m^2, and 405.17 W/m^2, respectively. Here, the total solar energy was 13.08 MJ/m^2. The ambient temperature shows similar trend with solar radiation. In the first half day, it increases over time and in the afternoon, it decreases over time. The minimum, maximum, and average temperatures were 29.69 °C, 35.87 °C, and 32.59 °C, respectively. The solar radiation and ambient temperature strongly affected temperature inside the drying chamber. This is because the hot air inside the drying chamber drawn from ambient air and heated by solar radiation. When the solar radiation fall down, the flow of hot air will be decreased. Thus, temperature inside the drying chamber will also be decreased. The minimum, maximum, and average temperatures in the drying chamber were 35.5 °C, 54.5 °C, and 45.06 °C, respectively. These facts reveal that temperature inside the drying chamber is higher than the ambient temperature with an average temperature difference of 12.5 °C. This temperature difference will provide sufficient thermal energy to drive drying process in the daytime. In addition, the maximum temperature inside the drying chamber is less than 60 °C that is a suitable drying condition for cocoa beans [2].

Fig. 3(b) shows temperature and humidity inside the drying chamber and ambient in the first nighttime. The ambient temperature varies over time with a maximum, minimum, and average temperatures of 31.3 °C, 24.79 °C, and 27.16 °C, respectively. Temperature inside drying chamber also varies, with maximum, minimum, and average temperatures of 38.5 °C, 25.5 °C, and 29.7 °C. The temperature inside the drying chamber is slightly higher than ambient temperature, the difference is only 2.61 °C. This temperature difference is too low to drive drying process. Humidity inside the drying chamber and the ambient are also shown in the figure. The minimum, maximum, and average humidity in the drying chamber were 13.14 g/kg air, 19.9 g/kg air, and 16.35 g/kg air, respectively. On the other hand, minimum, maximum, and average humidity of the ambient air were 18 g/kg air, 20.45 g/kg air, and 18.96 g/kg air, respectively. The humidity inside the drying chamber is relatively low. This will drive the drying process in the nighttime even though the sunshine is off. Fig. 3(c) shows drying conditions in the second daytime. It shows the same trend as in the first daytime. Minimum, maximum, and average solar radiations were 81.9 W/m^2, 760.6 W/m^2, and 313.88 W/m^2, respectively. Total solar radiation was 10.17 MJ/m^2. Temperature inside the drying chamber is higher than ambient temperature with an average temperature difference of 10.42 °C. In comparison with the first daytime, the temperature difference in the second daytime was lower. This is because total solar radiation was lower.

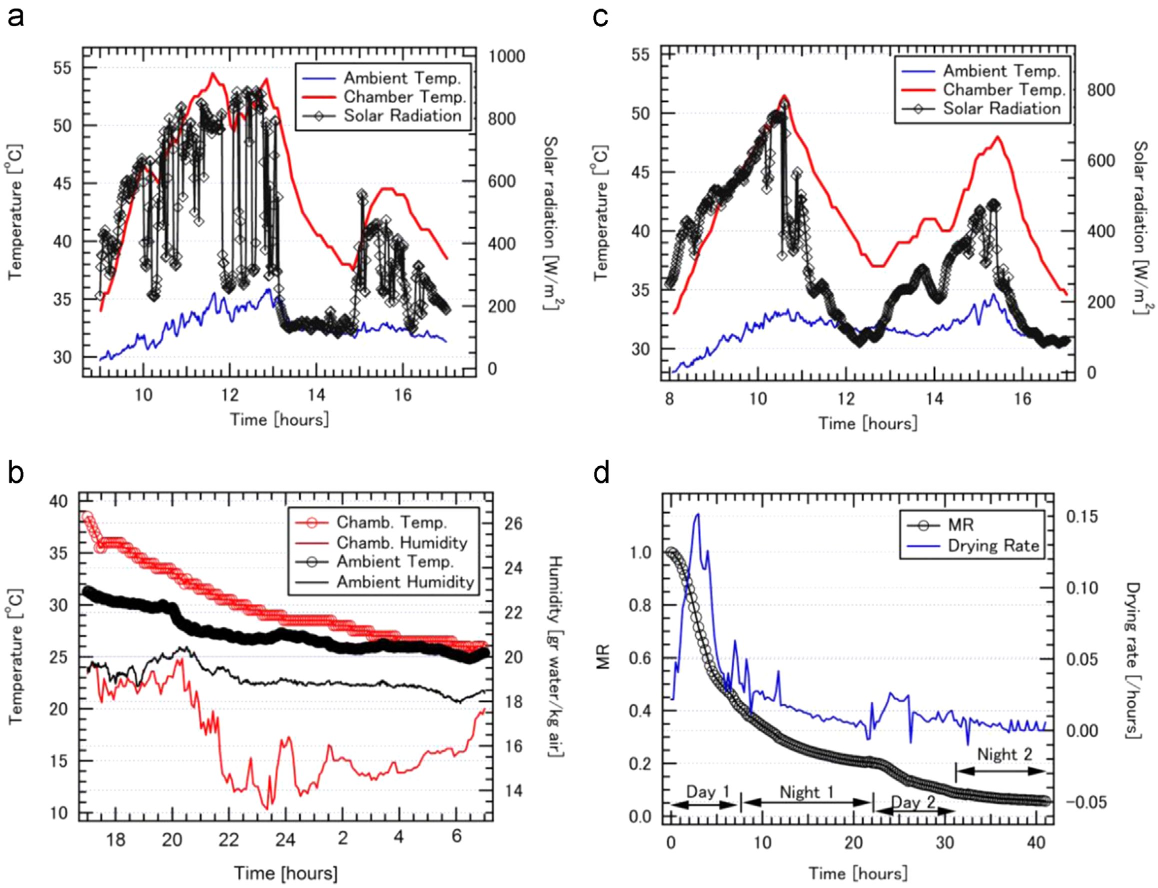


Fig. 3. Drying conditions of solar dryer integrated with adsorbent. (a) Day 1, (b) Nignt 1, (c) Day 2 and (d) MR and Drying rate.

Fig. 3(d) shows the non-dimensional moisture content (MR) and drying rate versus time of continuous drying with adsorbent. In the first daytime, MR decreased rapidly, from 1 to 0.4526 (54.74% reduction) and in the first nighttime, it decreased from 0.4526 to 0.19 (25.36% reduction). In the second daytime, it decreased from 0.19 to 0.09 (9% reduction). The drying rate is also shown in the figure. The drying process can be divided into two periods, a high drying rate period and falling rate period. Early hours of the first daytime can be categorized as high drying period. This is because the moisture content is high and present in the surface of the object. After this period, the moist inside the object (below the surface) will diffuse to surface, it needs time or the drying rate will be slowing. The figure clearly shows that the drying process occurs in the nighttime even though the sunshine is off. This is because of the presence of desiccant thermal storage inside the drying chamber the nighttime.

3.1.2. *Continuous solar drying with absorbent*

The drying experiments for continuous solar drying integrated with absorbent type thermal storage were also carried out. In general, the total drying time was two days and one night or total drying time was 30 h. Fig. 4 shows typical drying conditions. Fig. 4(a) shows solar radiation, ambient temperature, and temperature inside the drying chamber of the first daytime. The minimum, maximum, and average solar radiations were 59.4 W/m^2, 939.4 W/m^2, and 350.5 W/m^2, respectively. Total solar radiation was 11.35 MJ/m^2. The minimum, maximum, and average temperatures were 26.11 °C, 35.23 °C, and 31.16 °C, respectively. The minimum, maximum, and average temperatures in the drying chamber were 31.5 °C, 46.5 °C, and 40.05 °C, respectively. These facts show that temperatures inside the drying chamber are relatively higher than the ambient temperature with an average temperature difference of 8.9 °C. In comparison to first day of continuous drying with adsorbent, the average temperature in the drying chamber is relatively lower. This is because solar radiation during this experiment is lower.

Fig. 4(b) shows temperature and humidity inside the drying chamber and ambient air in the first nighttime. The maximum, minimum, and average temperatures of ambient were 24.07 °C, 30.85 °C, and 25.67 °C, respectively. Inside the drying chamber, the minimum, maximum, and average temperatures were 27.00 °C, 37.00 °C and 30.45 °C, respectively. These values reveal that temperature of the drying chamber is too low to drive drying process. The humidity inside the drying chamber varies from a minimum value of 9.39 g/kg air to a maximum value of 18.69 g/kg air. The average humidity was 13.05 g/kg air. These values show that humidity inside the drying chamber is low. This will provide a lower moist concentration at above the cocoa beans surface and it drives drying process, even though the sunshine is off. The comparison with the adsorbent type thermal storage discussed in the previous section, the average humidity in the drying chamber was lower. Fig. 4(c) shows ambient temperature, temperature in drying chamber and solar radiation in the second daytime. Minimum, maximum, and average solar radiations were 13.1 W/m^2, 969.4 W/m^2, and 473.54 W/m^2, respectively. The total radiation was 15.37 MJ/m^2. Temperature inside the drying chamber was higher than ambient with average difference of 12.31 °C.

Fig. 4(d) shows the non-dimensional moisture content (MR) history of continuous drying with absorbent. It can be seen that in the first daytime, the non-dimensional moisture content decreases rapidly, from 1 to 0.4526 (54.74% reduction). In the first nighttime, it decreases from 0.4526 to 0.19 (25.36% reduction) and in the second daytime it decreases in order of 9%. The drying rate is also shown in the figure. The figure clearly shows that the drying process occurs in the nighttime even though the sunshine is off.

3.2. Drying effectiveness

Fig. 5 shows MR versus time for all three drying methods including conventional direct sun drying. As a note, the conventional direct sun drying is a typical drying method used in Indonesia by smallholder farmers. The figure shows that total drying time for direct sun drying was 3 daytimes and 2 nighttimes or total 55 h. This is a typical drying time for cocoa beans in Indonesia with condition of clear sky radiation. A survey revealed that drying time in the farmers varies from three to five days [13]. It can be seen in the figure that during the night hours, there was no reduction of MR or drying process stops. However, using solar dryer integrated with thermal storage, the drying time was decreased. The drying time for solar dryer integrated with adsorbent was 41 h or 25% reduction in comparison with direct sun drying. The drying time for solar dryer integrated with absorbent, the drying time was only 30 h. It decreased up to 45.45%. These facts reveal that solar dryer integrated with desiccant is more effective in comparison with direct sun drying.

Comparison of both desiccants shows that the absorbent is more effective than the adsorbent. In the first nighttime, 120 g of water content from the cocoa beans has been evaporated by adsorbent. On the other hand, the absorbent one

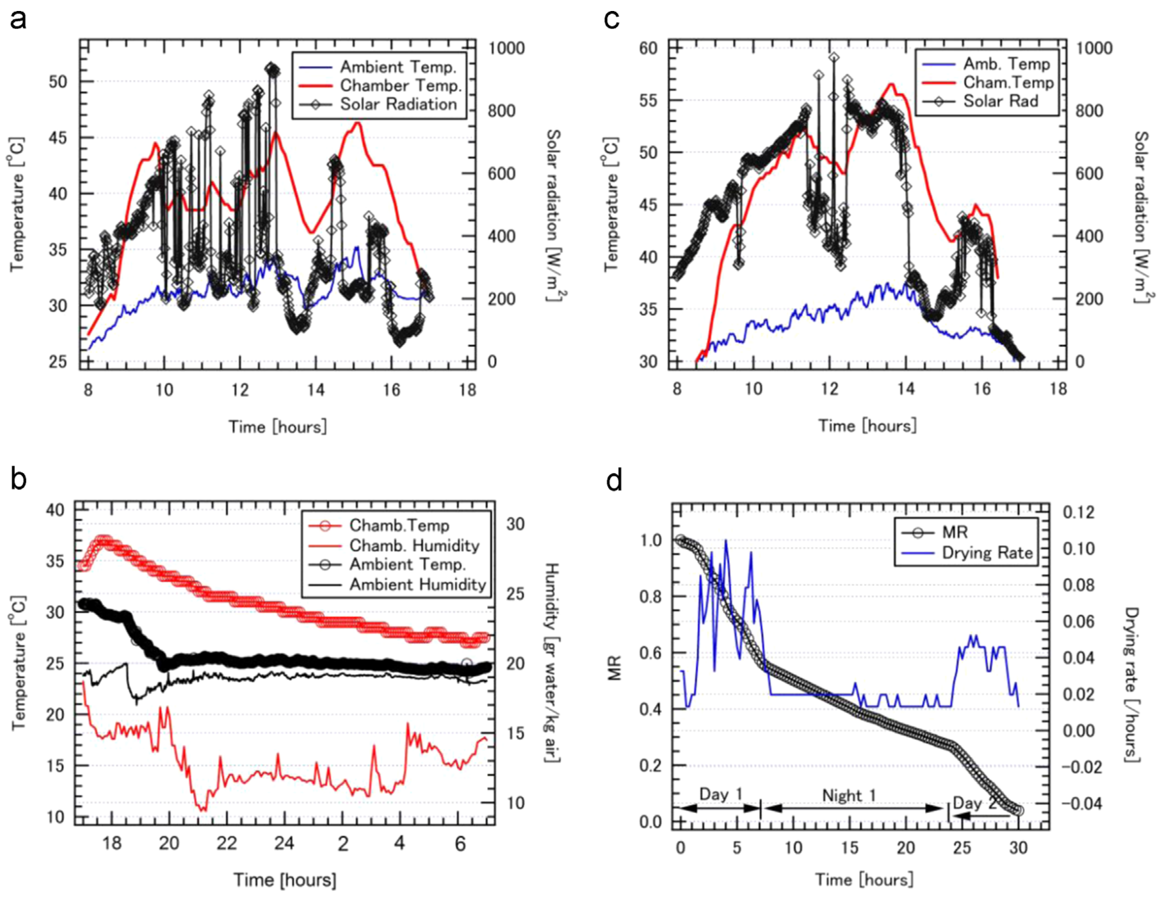


Fig. 4. Drying conditions of solar dryer integrated with absorbent. (a) Day 1, (b) Nignt 1, (c) Day 2 and (d) MR and Drying rate.

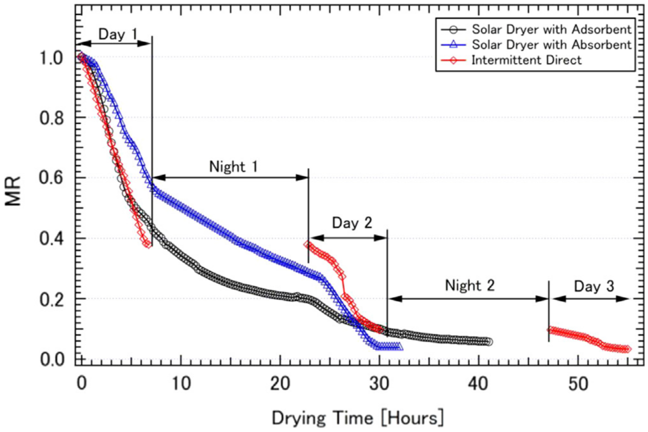


Fig. 5. Moisture contents versus time for all drying modes.

evaporated 170 g of water content. The stoichiometric and mass balance calculations to these desiccants show the reason. The adsorption using molecular sieve ($Na_2O \cdot Al_2O_3 \cdot 2.45SiO_2 \cdot 6H_2O$) has adsorption ability of 20.9%. However, the hydrate salt formed in the end of the absorption is $CaCl_2 \cdot 2H_2O$ which has absorption ability of 38.4%.

3.3. *Specific energy consumption*

The specific energy consumption has been defined in Section 2.4. It was formulated using Eqs. (2)–(11). It shows effectiveness on using energy for drying. The continuous solar dryer integrated with adsorbent desiccant evaporated 519 g of moist during 41 h of drying time. It consumed solar energy and thermo-chemical energy of 7.84 MJ and 1.99 MJ, respectively. Thus, the specific energy consumption was 18.94 MJ/kg. The solar dryer integrated with absorbent consumed solar energy and thermo-chemical energy of 7.84 and 0.068 MJ, respectively. It evaporated 595 g of moist during 30 h of drying time. The specific energy consumption was 13.29 MJ/kg. The intermittent direct sun drying consumed solar energy of 33.1 MJ to evaporate 548 g of moist. Here the specific energy consumption was 60.4 MJ/kg. These values reveal that solar dryer integrated with desiccant consumes less energy in comparison with direct sun drying. This is because of solar dryer provides a longer drying process even in the off-sunshine hours. The conclusion can be drawn here is that solar dryer with integrated desiccant thermal energy storage consume energy more effectively.

3.4. *Effective diffusivity*

Effective diffusivity is an overall mass transport property of moist which includes liquid diffusion, vapor diffusion, hydrodynamic flow, and other possible mass transfer mechanism. This parameter is an important parameter used to evaluate drying. It was calculated using Eqs. (12) and (13). By using 10 beans from each sample, average radius of cocoa beans in continuous solar dryer with adsorbent and with absorbent were, $r=0.00664$ m and $r=0.0068$ m, respectively. The effective diffusivity of cocoa beans dried by the solar dryer integrated with adsorbent was 9.63×10^{-11} m^2/s and the solar dryer integrated with absorbent was 8.94×10^{-11} m^2/s. The difference of this effective diffusivity is caused by the difference of the dimensions of cocoa beans. However, the effective diffusivity resulted in the present study is in the range resulted by Hii et al. [14] which varies from 7.46×10^{-11} to 1.87×10^{-10} m^2/s. The present effective diffusivity is comparable with artificial oven drying with temperature condition of 45 °C [13].

4. Conclusions

Effectiveness of continuous of solar dryer integrated with desiccant thermal energy storage has been studied experimentally. The average temperature within the drying chamber varied from 9 °C to 12 °C above the ambient temperature. The maximum temperature within the drying chamber varied from 40 °C to 54 °C. These temperatures are very suitable for drying cocoa beans. During the off-sunshine hours, desiccant type thermal energy storage made humidity within the drying chamber lower. These conditions continued drying process within the drying chamber during off-sunshine hours. The solar dryer integrated with desiccant type thermal energy storage make drying more effective. The experiments showed the traditional directs sun drying spent 55 h of intermittent drying. This drying time was reduced into 41 h (25% reduction) by using adsorbent type desiccant and it was 30 h (reduction 45.45%) by using absorbent type desiccant. The main conclusion here is that solar dryer integrated with desiccant thermal energy storage makes drying using solar energy more effective in terms of drying time and specific energy consumption.

References

[1] ICCO. Quarterly bulletin of cocoa statistics. Cocoa Book Year 2014;vol. XL(2).
[2] Jinap S, Thien J, Yap TN. Effect of drying on acidity and volatile fatty acids content of cocoa beans. J. Sci. Food Agric. 1994;65:67–75.
[3] Camu N, De Winter T, Solomon KA, Jemmy ST, Herwig B, Vuyst LD. Fermentation of cocoa beans: influence of microbial activities and polyphenol concentrations on the flavour of chocolate. J. Sci. Food Agric. 2008;88(13):2288–97.
[4] Bonaparte A, Alikhani Z, Madramootoo CA, Raghavan V. Some quality characteristics of solar-dried cocoa beans in St. Lucia. J. Sci. Food Agric. 1998;76(4):553–8.
[5] Hii CL, Law CL, Rahman RA, Jinap S, Che Man YB, Quality comparison of cocoa beans dried using solar and sun drying with perforated and non-perforated drying platform, in: Proceedings of the 5th Asia-Pacific Drying Conference, Hong Kong, 13–15 August 2007, pp. 546–52.
[6] Sharma A, Chen CR, Nguyen VL. Solar-energy drying systems: a review. Renew. Sustain. Energy Rev. 2009;13:1185–210.
[7] Fagunwa AO, Koya OA, Faborode. Development of an intermittent solar dryer for cocoa beans. Agric. Eng. Int.: CIGR J. 2009;XI:1–4 (Manuscript 1292).
[8] Jangam SV, Mujumdar AS, Basic concepts and definitions, in: Drying of Foods, Vegetables, and Fruits, vol. 1, Singapore, 2010, pp. 1–30.
[9] Lalit MB, Santosh S, Naik SN. Solar dryer with thermal energy storage systems for drying agricultural food products: a review. Renew. Sustain. Energy Rev. 2010;14(8).
[10] Butler JL, Troeger JM. Peanut drying with solar energy. Am. Soc. Agric. Biol. Eng.: Trans. ASABE 1980;23(5):1250–3.
[11] Devahastin S, Pitaksuriyarat S. Use of latent heat storage to conserve energy during drying and its effect on drying kinetics of a food product. Appl. Therm. Eng. 2006;26(14–15):1705–13.
[12] Shanmugam V, Natarajan E. Experimental study of regenerative desiccant integrated solar dryer with and without reflective mirror. Appl. Therm. Eng. 2007;27(8–9):1543–51.
[13] Dina SF, Napitupulu FH, Ambarita H. Study on varies drying methods of cocoa beans in Indonesia (in Bahasa). J. Ris. Ind. 2013;7(1):35–52.
[14] Hii CL, Law CL, Cloke M. Determination of effective diffusivity of cocoa beans using variable diffusivity model. J. Appl. Sci. 2009;9(17):3116–20.
[15] Ndukwu MC, Ogunlowo AS, Olukunle OJ. Cocoa bean (*Theobroma cocoa* L.) drying kinetics. Chil. J. Agric. Res. 2010;70(4):633–9.
[16] Doymaz I. Drying characteristics and kinetics of okra. J. Food Eng. 2005;69(3):275–9.