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# Performance testing of the tandem hybrid solar-biomass dryer for coffee cherry drying

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**Abstract** The results indicated that the temperature, relative humidity, and chimney air velocity of the front drying chamber were 59.8(±6.3)$^{o}$C, 27.5.6(±13.0)%, and 1.3(±0.44)m/s while the temperature, relative humidity and chimney air velocity of the rear drying chamber was 57.1(±6.1)$^{o}$C,73.0(±8.8)%, and 0.35(±0.07)m/s with the referent ambient temperature and relative humidity were 30.4(±2.1)$^{o}$C and 73.8(±9.9)%. The moisture content of the coffee cherries decreased drying time following a sigmoid-shaped curve model for all cherry samples of the bed thicknesses in both drying chambers. The coffee cherry drying process for the front drying chamber was faster than that of the rear drying chamber. The time to complete the drying process marked by the green bean maximum moisture content of 12% for the bed thicknesses of 3, 6, 9, and 12 cm were 58.7 h, 62.3 h, 73.8 h, and 86.9 h respectively for the cherry samples in the front drying chamber and 71.0 h, 80.8 h, 88.7 h and 91.4 h for the cherry samples in the rear drying chamber suggesting that the dryer needed to be further explored for a wider range of drying temperature, cherry bed thicknesses, and the result in coffee beans quality leading to adoption for the users.

**Keywords:** Bed thickness, Drying time, Moisture content, Temperature, Velocity

## Introduction

Drying is a very important process in producing coffee green beans. There are three ways of processing coffee cherries to produce coffee green beans, namely natural or dry processing, fully washed, and semi-washed. However, the majority of farmers in Indonesia choose the dry processing method by placing the harvested coffee cherries in the open air under the hot sun which is called sun drying. Drying this way takes 2-3 weeks to produce dry coffee green beans. The length of time required to complete the drying process is allegedly the cause of the inferior quality of coffee green beans produced from smallholder plantations.

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To overcome this problem, various types of coffee dryers, ranging from solar dryers (Putra and Hadi, 2013, Widyotomo, 2014; Firdissa *et al*., 2022, Gachen *et al.,* 2020, Dina *et al.,* 2018, Hudin *et al*., 2021), hybrid solar dryers (Irwansyah *et al*., 2017, Yani and Fajrin, 2013, Agustina *et al*., 2016, Sutrisno *et al*., 2020, Gunawan *et al*., 2021, Nasrin *et al*., 2021, Suherman *et al*., 2020), mechanical dryers (Murdianto and Santoso, 2019, Hidayat *et al*., 2018, Hamni *et al*., 2014, Prasetya *et al*., 2020, Nasrin *et al*., 2021, Phitakwinai *et al*., 2019, Muhidong *et al.,* 2013, Firdissa *et al.,* 2022) have been developed and investigated. Some solar dryers are equipped with fans or blowers to help circulate hot air in the drying chamber, while in hybrid dryers and mechanical dryers a fan or blower is used to circulate hot air from the furnace or heater into the drying chamber. Heat substitution for the hybrid dryer is possibly in the form of biomass combustion heat, LPG heat, heat from electric heaters, or heat from heat exchangers.

In general, the performance of the dryer is determined by its size, temperature, and drying air velocity. In terms of the solar dryer, the size of dryers ranges from less than 1 $m^2$ (Hudin *et al.*, 2021) to 432 $m^2$ (Widyotomo, 2014, operate with temperatures from 35$^o$C (Dina *et al.*, 2018, Firdissa *et al*., 2022) to 78$^o$C (Dina *et al*., 2018), and drying air velocity from 0,1 m/s (Hudin *et al.,* 2021) to 6 m/s (Dina *et al*., 2018. The dryers were tested using a drying capacity of 29 kg (Putra and Hadi, 2013) to 38,8 tons (Widyotomo, 2014. The initial moisture contents of samples being tested are from 55% (d.b) (Gachen *et al*., 2020) to 64% (d.b) (Widyotomo, 2014), and the final moisture contents varied from 11% (Gachen *et al*., 2020) to 12,5% (Dina *et al*., 2018), and drying time of 10 h (Dina *et al.,* 2018) to 14 days (Widyotomo, 2014).

The reported hybrid solar dryers included the size of 0,15 m2 (Irwansyah *et al.,* 2017) to 24 m2 (Chan *et al*., 2020) with a capacity of 5 kg to 800 kg coffee beans or cherries, worked in the temperature range of 37$^o$C to 60$^o$c and drying air velocity of 0,21 to 0,6 m/5, and the completed drying process in 3 – 7 days.

Mechanical dryers for coffee drying covered several types and capacities, such as a batch of 40 kg of coffee beans (Murdianto and Santosa, 2019), a mason dyer of 20 tonnes of coffee beans (Hidayat *et al*., 2018), and dryer assisted with gasification reactor of 400 kg coffee cherries (Hamni *et al.,* 2014), roll dryer (Prasetya *et al*., 2020) and vertical mixed flow dryer (Sutrisno *et al*., 2020) of 1 kg coffee beans per run. These dryers operated in the range of temperatures from 55$^o$C to 120$^o$C.

Although some solar dryers have been equipped with heat storage devices, they are still faced with problems due to bad weather since they rely on sunlight. On the other hand, hybrid solar dryers are highly dependent on the availability of electricity to operate fans or blowers to deliver heat from an additional heat source and to circulate the hot air in the drying chamber. This becomes a problem because of getting higher electricity tariffs and when the dryer needs to be operated in an area with no electricity grid. Hybrid solar dryers also experience heat loss carried by the flue gases of the furnace chimney. On the other hand, the main constraint of mechanical dryers is the high cost of manufacture and operation.

An innovative dryer is needed as one of the solutions to the problems mentioned above. The purpose of this study was to introduce a tandem hybrid solar-biomass dryer and to explore its performance when the dryer was operated with solar heat and firewood combusting heat simultaneously to dry coffee cherries with different bed thickness, in the form of profiles of temperature and relative humidity in the drying chamber, drying air velocity, the curve of moisture content, and time to complete drying process with the coffee cherry moisture content of 12% as the indicator.

The objectives were to identify the profiles of temperature, solar radiation intensity, relative humidity, and drying air velocity as a function of drying time for the front and rear drying chambers, to determine the model of the moisture content curve as the drying time associated with the drying chamber and the thickness of the coffee bed, and to examine the influence of the drying chamber and the cherry bed thickness against the time to complete the drying process.

## Materials and methods

The study was conducted at the Agricultural Technology Laboratory, Agricultural Technology Department, Faculty of Agriculture, Bengkulu University, where the dryer was installed, from July to August 2022. The dryer consisted of two drying chambers, front and rear, each of which is equipped with a chimney and two doors, and contained 10 racks which were arranged into five levels (5 right and 5 left). The front drying chamber is equipped with 2 heat collectors. A furnace is located below with a heat storage and exchanger located in the drying chamber, and a furnace wall itself as a heat exchanger.

The dryer was operated with solar heat and heat from the combustion of firewood simultaneously. Based on a preliminary study, to produce a rear drying chamber temperature that did not harm the coffee cherries, the furnace was ignited with an initial supply of 5 kg of firewood and a follow-up supply of 4 kg every 20 minutes.

The dryer operated as follows: the heat that enters the heat collector plenum is collected by the collector plate which is used to heat fresh air that enters through the heat collector inlet which then flows into the drying chamber. This hot air gets additional heat from two sources, namely solar heat entering through the roof and walls of the front drying chamber and heat from the heat storage and exchanger which is transferred from the furnace. The drying chamber also gets a supply of hot air from a duct coming from the furnace wall. All the hot air supplied to the drying chamber flows through the drying racks containing the wet coffee cherries to evaporate the water and then the resulting moist air is discharged from the drying chamber through the front chimney outlet. Meanwhile, in the rear drying chamber, exhaust gas from the furnace chimney flows and passes through the drying racks containing wet coffee cherries and evaporates the cherry moisture content and then the resulting moist air is discharged through the rear chimney outlet.

The dryer was tested to dry coffee cherries with bed thicknesses, namely 3, 6, 9, and 12 cm, employing the Split Plot Design Experiment in which the drying chamber was the main plot, the bed thickness was the split-plot, and the rack's level as replication, to investigate the effect of drying chamber and bed thickness on the time to complete drying process ($t_c$) i.e. cherry's moisture content of 12%. Red coffee cherries selectively picked from smallholder plantations in Sindang Dataran District, Rejang Regency, Bengkulu Province, having a bulk density of 607.66($\pm$4.55) kg/m$^3$) were used in the experiment.

Forty sample boxes made of nylon-coated wire nets, divided into 10 series, each containing 4 boxes were prepared to be filled with coffee cherries with bed thicknesses of 3, 6, 9, and 12 cm. Five series boxes were placed on the front drying chamber racks at different levels, series 1 on the level 1 right rack, series 2 on the level 2 left rack, series 3 on the level 3 right rack, series 4 on the level 4 left rack, and series 5 on level 5 right rack. The other five series were placed on the rear drying chamber racks in the same manner. Once all the sample boxes were in place, all the rack areas around the sample boxes were filled with coffee cherries. In addition to the sample box on the same rack, a digital thermometer sensor was placed to measure the temperature of the drying air. The drying operation started at 9 am and ended at 10 pm. The variables observed were sample weight, drying chamber air temperature and relative humidity, ambient air temperature and relative humidity, sunlight intensity inside and outside the front drying chamber, and chimney air velocity of both drying chambers. Drying was continued the next day until the coffee cherries became dry, the sample boxes of the front drying chamber were taken out at the end of each observation. At the end of the drying process, samples of dry coffee cherries from all boxes of samples were prepared to measure the moisture contents by the oven method. The dry coffee cherry's moisture contents were calculated on a wet basis.

Sample weights were observed at 2-hour intervals while the other variables were at 30-minute intervals. Digital balance CAMRY Model: EK5055 High Precision was used for sample weighing. ScienPro-LT-5000 Model solarimeter was used to measure solar radiation intensity inside and outside the dryer. Twenty-one digital thermometers (TMP-10 model) with 0.1% resolution 0.1$^{o}$C were provided to measure the drying air temperature in the front (10 units, 1 for each rack level) and rear (10 units, 1 for each rack level) drying chambers, and ambient air (1 unit). Three digital thermo-hygrometers (HTC-2 Model) were placed inside the front (1 unit) and rear (1 unit) drying chambers and outside dryer (1 unit) to measure drying air relative humidity. A digital anemometer (Hold Peak Model 866B) was employed to measure drying air velocity in the chimneys of the front and rear drying chamber.

Data were averaged and presented in a graph with the function of drying time for temperature, relative humidity, solar radiation intensity, air velocity, and cherry's moisture content. The curve of moisture content as a function of drying time was described to identify the curve's model and to track the drying time to reach the cherry's moisture content of 12%. The regression analysis ready used in Microsoft Excell was used to analyze the relationships between the cherry's moisture contents and drying time, and between the time to complete the drying process and bed thickness of coffee cherries. Analysis of Varian (ANOVA) and Duncan Multiple Range Test (DMRT) with significant levels of 5% employing SPSS Statistic Software Version 23 was used to analyze the data of the time to complete the drying process.

## Results

The results of the experiment are in the form of curves of temperature, solar radiation intensity, relative humidity, and drying air velocity as a function of drying time.

### *Drying air temperatures*

Average drying air temperatures of the front and rear drying chambers together with ambient air temperature plotted against drying time are shown in Figure 1.

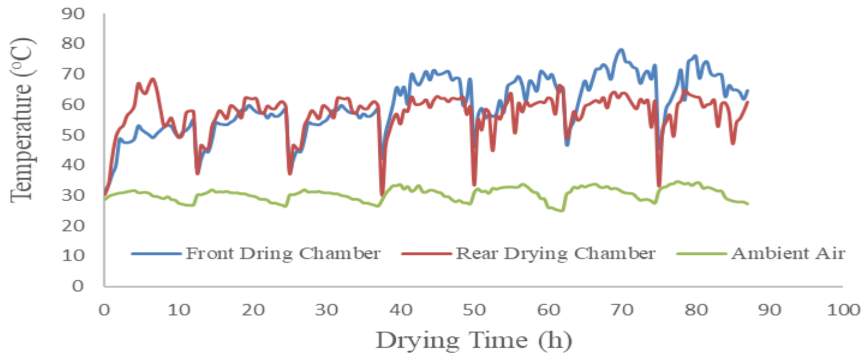


**Figure 1**. Temperatures of the drying chambers and ambient air plotted against drying time

### ***Solar radiation intensity***

Solar radiation intensities measured inside and outside of the front drying chamber during day times of the experiment are presented in Figure 2.

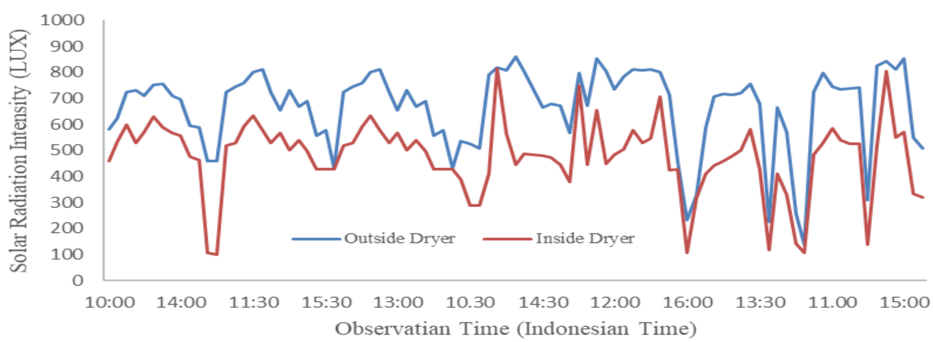


**Figure 2**. Solar radiation intensity values inside and outside dryer

### ***Drying air relative humidity***

Drying air relative humidity values of the front and rear drying chambers together with ambient air relative humidity values plotted against drying time are presented in Figure 3.

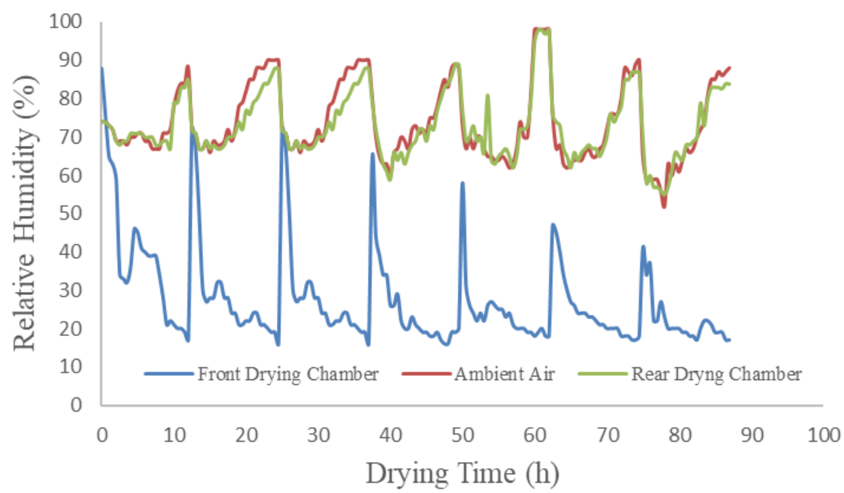


**Figure 3**. Relative humidity values of the drying chambers and ambient air plotted against drying time

***Drying air velocity***

Drying air velocities measured in the chimneys of the front and rear drying chamber plotted against drying time are presented in Figure 4.

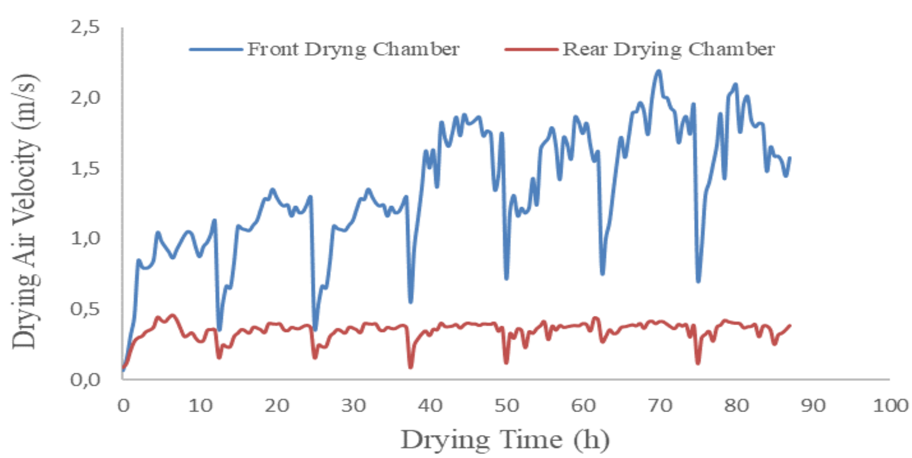


**Figure 4**. Drying air velocity plotted against drying time

### *Curve models of coffee cherry moisture contents*

Coffee cherry moisture contents were averaged according to the sample's bed thicknesses and the average values were then plotted against drying time to find the best-fitted equation models of the curves. The relationships between coffee cherry moisture contents and drying time together with their equation models for the front and rear drying chambers are shown in Figures 5 dan 6.

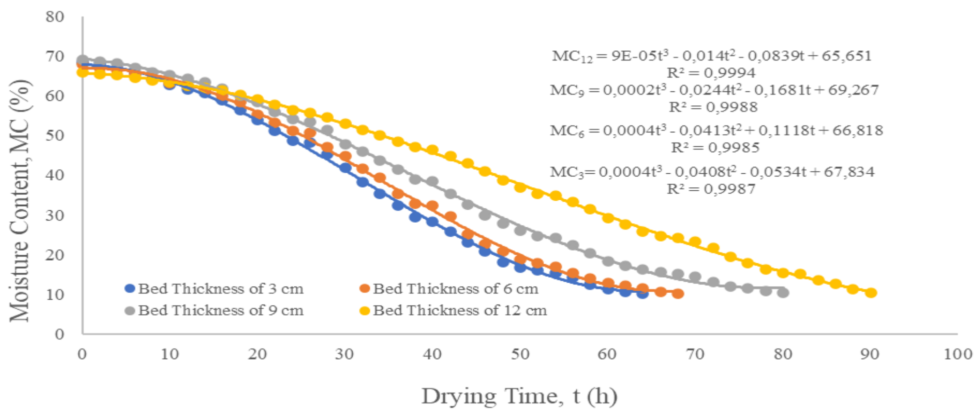


**Figure 5.** Coffee cherry's moisture content of the front drying chamber plotted against drying time

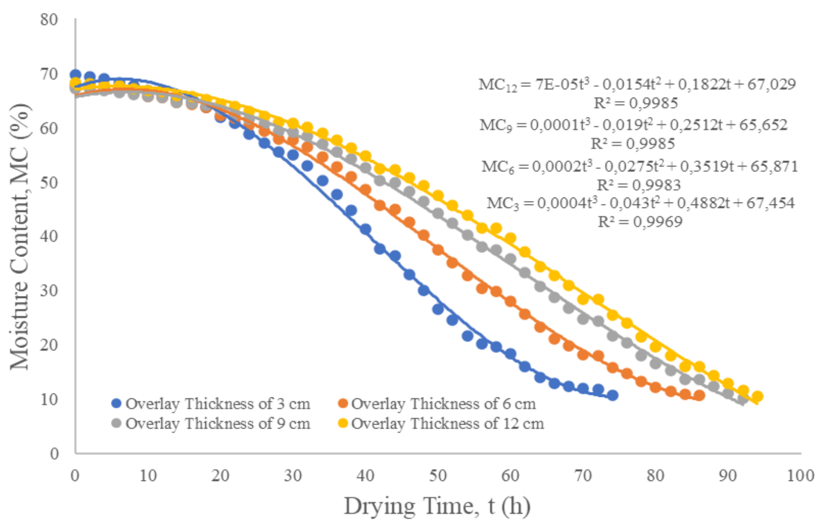


**Figure 6**. Coffee cherry's moisture content of the rear drying chamber plotted against drying time

### *Time to complete the drying process*

Using 12% coffee cherry moisture content, the time to complete the drying process for every bed thickness of coffee cherry was interpolated from the moisture content data versus drying time for each rack level as replication. The times to complete the drying processes are presented in Table 1.

**Table 1**. Times to complete drying process ($t_c$)

| Drying Chamber | Bed Thickness | Time to complete the drying process, $t_c$ (h) Replication | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| Front | 3 cm | 50.2 | 56.0 | 63.0 | 60.4 | 64.0 |
| | 6 cm | 56.8 | 63.6 | 62.5 | 64.7 | 64.1 |
| | 9 cm | 72.2 | 68.6 | 78.5 | 71.3 | 78.3 |
| | 12 cm | 83.6 | 87.0 | 89.5 | 87.4 | 86.9 |
| Rear | 3 cm | 77.0 | 76.0 | 77.9 | 62.9 | 61.3 |
| | 6 cm | 86.7 | 86.5 | 88.8 | 79.1 | 62.8 |
| | 9 cm | 93.2 | 92.8 | 92.9 | 88.6 | 76.0 |
| | 12 cm | 94.3 | 93.8 | 95.0 | 90.5 | 83.3 |

### *Effects of drying chamber and cherry bed thickness on time to complete the drying process*

ANOVA was employed by using Split Plot Design for the time to complete the drying process, in which the drying chamber and the coffee cherry bed thickness were the main plot and the sub-plot respectively and the result is given in Table 2.

**Table 2.** ANOVA results for the time to complete the drying process ($t_c$)

| Source of Variation | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Replication | Hypothesis | 342.775 | 4 | 85.694 | .463 | .763 |
| | Error | 739.769 | 4 | 184.942[a] | | |
| Drying Chamber | Hypothesis | 1572.516 | 1 | 1572.516 | 8.503 | .043 |
| | Error | 739.769 | 4 | 184.942[a] | | |
| Drying Chamber x Replication | Hypothesis | 739.769 | 4 | 184.942 | 20.214 | .000 |
| | Error | 219.576 | 24 | 9.149[b] | | |
| Coffee Bed Thickness | Hypothesis | 3414.850 | 3 | 1138.283 | 124.416 | .000 |
| | Error | 219.576 | 24 | 9.149[b] | | |
| Drying Chamber x Coffee Bed Thickness | Hypothesis | 262.934 | 3 | 87.645 | 9.580 | .000 |
| | Error | 219.576 | 24 | 9.149[b] | | |

Note: A number followed by a different letter is significant

Since the effect of the coffee cherry bed thickness on the time to complete the drying process was significant, the average values of the times to complete the drying process for the front and rear drying chambers were re-averaged to perform DMRT, and the result is presented in Table 3.

**Table 3.** DMRT for the time to complete the drying process ($t_c$), h

| **Coffee Bed** | | **Subset** | | | |
|---|---|---|---|---|---|
| **Thickness** | **N** | 1 | 2 | 3 | 4 |
| 3 cm | 10 | 64.87 | a | | |
| 6 cm | 10 | | 71.56 | b | |
| 9 cm | 10 | | | 81.24 | c |
| 12 cm | 10 | | | | 89.13d |
| Sig. | | 1.000 | 1.000 | 1.000 | 1.000 |

Note: A number followed by a different letter is significant

***Time to complete the drying process versus coffee cherry bed thickness***

Data in Table 1 were averaged according to the coffee cherry bed thickness together with data in Table 3 were plotted against drying, and the result is presented in Figure 7.

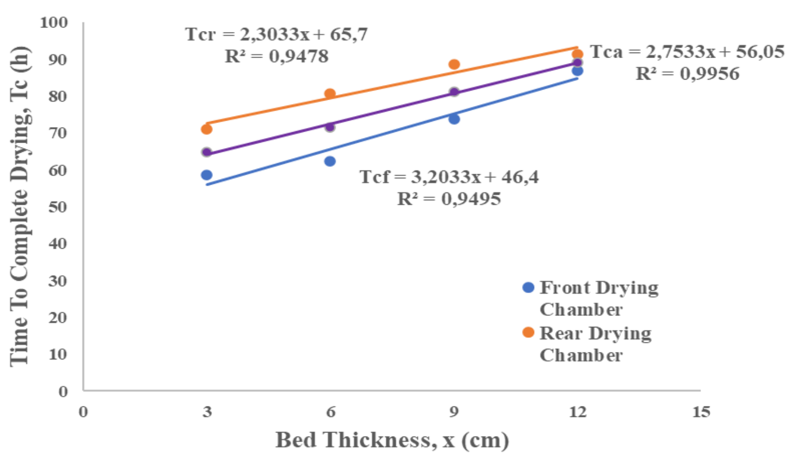


**Figure 7**. Time to complete drying process plotted against bed thickness

## Discussion

From the experimental results, some important aspects can be derived. The temperatures of the front and rear drying chambers were 59.8(±6.3)$^o$C and 57,1(±6.1)$^o$C respectively whereas the ambient temperature was 30.4(±2.1)$^o$C. The temperature of the front drying chamber influenced the supplied heat from solar radiation where the higher the radiation intensity was the higher the front drying chamber temperature. These drying air temperatures approached the drying air reported by Gunawan *et al*. (2021), Phitakwinai *et al*. (2019) and Irwansyah *et al.* (2017) were higher than the drying air temperature explored by Dina *et al*. 2018, Firdissa *et al.*, 2022 (35$^o$C) but lower than that of investigated by Dina *et al.* 2018(78$^o$C). The relative humidity values of the front and rear drying chambers were 27.5(±13)% and 73(±8.8)% while the ambient relative humidity was 73.8(9.9)%, and no drying air humidity was reported by researchers. The drying air velocities of the front and rear drying chambers were 1.35(±0,44) m/s and 0.35(±0.07) m/s. which were higher than the drying air velocities reported by Hudin *et al.* (2021) and Chan *et al.* (2020) but lower than those investigated by Dina *et al.* (2018). The coffee cherry moisture contents in both front and rear drying chambers decreased with drying time, following a sigmoid curve model with a polynomial equation of third order. This typical model of the curve was contradicted by the Page model reported by Gunawan *et al.* (2021) and Suherman *et al*. (2020), the Midilli model observed by Phitakwinai *et al.* (2019), and the Hii model explored by Muhidong *et al.* (2013).

The performance of this dryer can be evaluated by comparing it with the dryer reported by Chan *et al*. (2020). The structure of the Chan dryer building has drying chamber dimensions of 8 m long, 3 meters wide, and 2.4 m high, contains 4 shelves with a size of 5.9 m x 1.15 m, and is equipped with a furnace with a size of 1.2 m x 1.2 m x 1.3 which is outside the drying room, so the total area is 25.44 m$^2$. This dryer was operated by the sun's heat and followed by the heat of burning firewood with a supply of 5 kg every hour for 11.33 hours per day and produced an average temperature of 43.6$^o$C and completed drying of 800 kg of coffee cherries for 7 days or 79.3 hours, reduced moisture content from 65% to 12%. On the other hand, this dryer consists of two drying chambers with a total size of 2 m x 4 m x 1.55 m containing 20 racks with a size of 0.87 m x 2 m and a heat collector with a horizontal area of 3.5 m x 2 m so that the total area is only 15 m$^2$. By employing this dryer 800 kg of cherry coffee and by using a mass density value of 607.66 kg/m3 which is only equivalent to a layer thickness of 3.783 cm and by using the Tca equation drying can be completed in 66.47 hours, decreased moisture content from

67.9% to 12%. This dryer can complete the drying process faster than the Chan dryer.

Based on the above results some findings can be highlighted as follows. The coffee drying process of the front drying chamber was faster than that of the rear drying chamber. The water content of coffee cherries decreased with time following a sigmoid curve model with a polynomial equation to the power of three. The shape of the curve was the convex upward curve at the beginning of the drying process might be due to moisture in the mucilage having difficulty in penetrating the coffee cherry skin layer which is covered by a layer of natural wax. After this wax layer became penetrable, the water content of cherry coffee decreased quickly so that the curve trend became concave downwards and then convexes downwards again when the moisture content approached 10%. The time to complete the drying process(tc) increased linearly with the thickness of the bed with a fairly gentle slope, which indicated that the thicker the bed was the more efficient the drying process. The advantages of this dryer are that it can reduce heat loss in the system and does not require electricity to operate, can be operated anytime and anywhere, can use abundant, inexpensive, and renewable fuel, and has a larger capacity. The dryer needs to be further tested at a wider drying temperature range, and larger bed thicknesses, and to examine the quality of the dry coffee beans produced so that it is ready for adoption by users.

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