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RESEARCH ARTICLE

Experimental of Environmental Development Using Continuous Solar Dryer With Solid Dehumidification For Coffee Drying

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Abstract

As the tropical country, Indonesia has a sustainable solar energy for the farm products such as coffee. Indonesia's coffee has been categorized as one of the biggest export products in the world and needs a development system to provide drying coffee beans with good quality. Therefore, this study comprehensively explains an experiment to develop a continuous solar air dryer with a hybrid system for drying coffee. The system has two different modes: off-sunny and sunshine hours. The heated air from the collector is driven into the drying chamber during the sunlight. The results show that the drying chamber's maximum temperature during daylight ranged from 40°C to 56°C and 9°C to 22°C warmer than the ideal environment temperature. Then, the coffee beans got the 12,7% moisture content in 107 hours in a solar dryer with solid dehumidification material. During off-sunlight, the air humidity reaches a 17% reduction and relatively consistent with air temperature. Furthermore, the benefit of this research can support the agricultural system without sunlight and apply a molecular sieve as a solar dehumidifier for the desiccant material in the drying chamber.

Keywords: coffee bean, artificial dryers, drying, dehumidification, agricultural, desiccant, solar

1. Introduction

As the tropical country, the commodities of coffee product in Indonesia have been leading in South East-Asia region. Indonesia has dynamic environment process from climate, weather and earth interaction condition such as earthquake, tsunami and landslides that can be important for the sustainable farm infrastructures (Byrareddy et al., 2019; Pasari et al., 2021a, 2021b; Gunarya et al., 2024; Lubis et al., 2025). As example, the highest rainfall in Indonesia (see Figure 1), can provide more water for the soil quality and bring some minerals while low rainfall can provide more sunshine that can be used for solar energy (Muhajir et al, 2021; Lubis et al., 2024). However, the balance of both seasons is important due to difference behaviour of coffees variants (Bunn et al., 2015, Schroth et al., 2015). It is widely accepted that wet coffee processing preserves the beans' original flavours and sensory qualities, producing higher-quality coffee. The procedure may differ from farmer to farmer and typically consists of the following steps: selective harvesting to separate ripe berries, pulping to remove the fruit's inner and outer skins, mucilage removal via natural or enzyme-accelerated degradation (fermentation), or mechanical means, followed by washing and drying (Elhalis et al., 2021). Coffee can be used for health issues and treatment for several medical issues (Lamonge et al., 2024). The average moisture content of wet parchment coffee after washing ranges from 53-55% (Bottazzi et al., 2012). The challenging part is the quality of dry coffee that can be reduced to 10 - 12% and does not meet the commercialization criteria such as growth of germs, mycotoxins and maintaining the quality and safety of the product (Batista et al., 2009).

Sun drying had been a popular method for several decades due to environmentally or economically viable than fossil fuel-based energy for drying. However, there are various issues with the conventional open-air drying method, including long drying times, quality degradation, spoilage risks, and labour-intensive requirements (Lakshmi et al., 2018). While artificial desiccation methods gained popularity with mechanization, it may become expensive and energy-intensive. As a result, solar dryers have been a more practical option to deal with the drawbacks of conventional and artificial drying. Solar energy can save the sustainable energy that provide several benefits such as, shorter drying times, smaller drying spaces, and more effective process execution (Philip et al., 2022). Further interest in solar energy is globally needed for dried agricultural products, medicinal plants, and marine products that can provide a high-quality standard.

An efficient solar dryer technique can produce hot drying air at 10 – 25°C hotter than the surrounding air. The solar energy is naturally sporadic and largely reliant on the local weather conditions (Sharma et al., 2009). When there is no sunlight throughout the night, the ambient temperature lowers and the relative humidity increases. Therefore, there is a chance that dried items will reabsorb moisture, which could result in longer drying durations and, in the worst case, mold growth (Agrawal and Sarviya, 2016). Several studies have suggested a modern strategy using continuous drying to mitigate or lessen these sporadic impacts and have proposed a thermal storage material into solar dryers to save extra heat during the daylight and use it for drying at night (Zhou et al., 2013, Wray and Ramaswamy, 2015). Extrasolar thermal energy can be efficiently stored in well-insulated fluids or solids through sensible heat, latent heat, thermos chemical reactions, or a combination of these (Suresh and Saini, 2020). Thermal storage materials for drying food and agricultural goods have been globally used as the subject of several research studies (Zhou et al., 2013; Raba et al., 2018, Grzelczyk et al., 2022; Kovac et al., 2014).

One of the most cases of dehumidification techniques for solar drying is the regenerated desiccant material. The current trend in continuous solar drying involves including desiccants in the drying process when sunlight is not available (Dake et al., 2021). Several studies used desiccants such as silica gel, borax and maize meal has shown excellent product quality in color, texture, and durability (Chua and Chou, 2003; Raba et al., 2018). Drying slices of mushrooms (Agaricus bisporus) using desiccant dehumidifiers can assess the quality of the mushrooms structure, chemical composition, and therapeutic properties (Zhang et al., 2023). Kamm et al., (2002) explored how adding a silica gel adsorption unit affected the drying of apricots, finding that it increased quality, cut drying time from 52 to 44 hours, and was also cost-effective. Furthermore, the aim of this study is to create a continuous solar drier for agricultural products and incorporates a desiccant for dehumidification. When there is no sunlight, a molecular sieve acts as a solar dehumidifier for the desiccant material in the drying chamber. There is less studies prior of dehumidifying coffee beans process that can be useful for further development of agricultural infrastructures. Therefore, the benefits of this study can provide a new insight and detailed comparison about the dry-run machine for the coffee process with sunlight as well as with off-sunlight.

2. Methodology

The raw material used in this study is arabica coffee beans with moisture content of 55%. They were taken from UKM (Small and Medium Enterprises in Indonesia) in Arabica coffee beans from Toba Regency's Marsangap Village, North Sumatra, Indonesia.

2.1 Experimental setup

The experimental setup for the current investigation was created and built at the University of Sumatera Utara in Medan, Indonesia. This experimental setup had a fan blower, drying chamber, and collector. The components of this test design include a collection, drying chamber, solar panel, and blower fan. With two tilted angles of 30° and 180°, the collector has dimensions of 2200 mm in length, 1100 mm in breadth, and 150 mm in thickness. A transparent cover is utilized to stop heat leakage from the top of the collector double glass cover. The drying chamber has measurements of 1120 mm, 1150 mm, and 1000 mm and a blower fan system to move hot air from the solar collector as shown in Figure 2. The blower fan system is combined with a polycrystalline 50 WP solar panel with dimensions of 50 mm, 50 mm, and 50 mm.

An experiment was carried out on dried coffee beans to investigate the impact of continuous solar drying on dryer performance. The system includes a shade in all directions and pointed southward to maximize solar energy impacting the solar collector. The layer of beans is forced with hot air from the flat plate solar collector. A 5000-gram desiccant is positioned inside the drying chamber during the times when the sun is not shining. The chamber's temperature, surrounding humidity, coffee beans's weight loss and solar insulation are all factors that can be used to determine the system's performance. Moreover, five thousand grams of wet coffee beans on the drying rack are used for the drying trial during experiment as shown in Figure 3. The drying procedure is carried out until the product's equilibrium moisture is reached. The drying items' initial and final moisture contents are measured using the oven method. Coffee beans have an equilibrium moisture level of 54% and an initial moisture content of 12%, respectively. Testing happens between 7:00 PM and 7:00 AM and between 8:00 AM and 6:00 PM.

Fig. 2 - Image of the prototype solar drier for drying coffee figures out the systems such as photovoltaic, drying chamber, solar collector, air inlet, air outlet, data acquisition system and laptop to record the dry process.

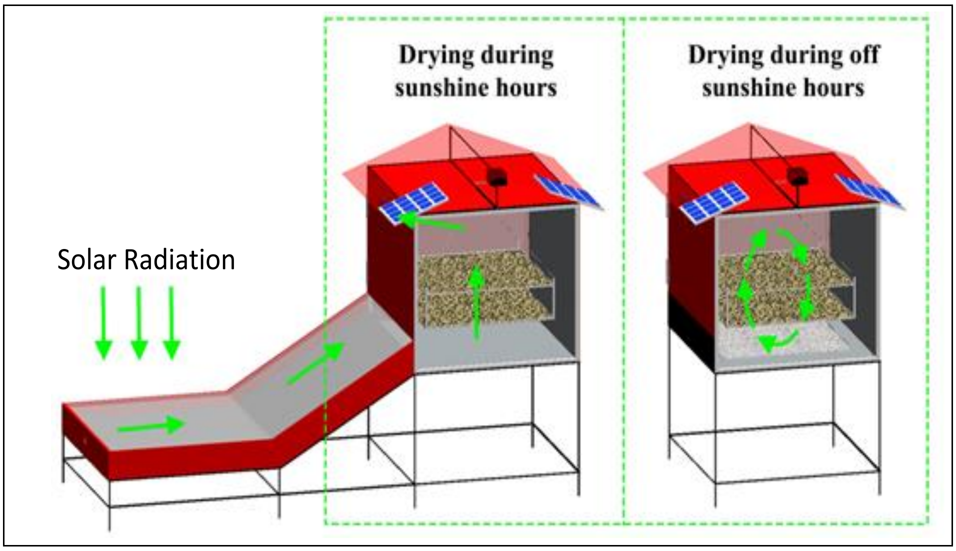

Fig. 3 - Schematic cartoon to explain the experiment setup process of coffee beans during daylight and off-daylight. The step is started with the solar radiation and continuously to the drying system. The heat from daylight activities can be used in the coffee drying process during night-time.

Fig. 4 - The condition inside drying chamber machine shows coffee beans process (a) during sunshine hours, and (b) during odd sunshine hours.

2.1 Selection of dehumidification

The water vapour adsorption theory underlies the operation of the molecular sieve 13-XAPG (SiO_2 and Al_2O_3). Due to the difference in partial pressure of water vapour between the surface of the solid desiccant and the process air, moisture in the air is extracted by the solid desiccant. As the process progresses, the desiccant becomes saturated and causes the dryer's dehumidification steadily declined. It must be remanufactured with high temperature and low moisture content airflow to operate and keep their increased efficiency. Solar energy can be used to create this regeneration/reactivation air.

2.2 Performance analysis parameters

The humidity rate determines the amount of water vapor and other volatile components in a given sample. The initial moisture content of the dry base was the weight of the product per unit. The weight of the dry matter in the product is the definition of the instantaneous moisture content at any given time.

3. Results And Discussion

The drying process generally spanned five daylight periods and four night time periods, resulting in a total drying time of 108 hours. The solar radiation conditions during the testing (see Figure 4). The outcomes show the history of solar radiation from the first to the fifth day. There are noticeable variances in the five radiation intensity conditions' values. It is evident that solar radiation rises throughout the day and then falls in the afternoon due to cloud cover during the testing. The minimum, maximum, and average solar radiation on the first day were 1.90 W/m2, 253.10 W/m2, and 150.77 W/m2, resulting in a total solar energy of 9.85 MJ/m^2. On the second day, the corresponding parameter values were 0.60 W/m^2, 360.60 W/m^2, and 139.20 W/m^2, with a total solar energy of 9.28 MJ/m^2. On the third day, the values were 0.60 W/m^2, 399.40 W/m^2, and 148.35 W/m^2, yielding a total solar energy of 9.76 MJ/m^2. On the fourth day, the values were 1.90 W/m^2, 516.90 W/m^2, and 248.24 W/m^2, resulting in a total solar energy of 15.10 MJ/m^2. On the fifth day, the values were 23.10 W/m^2, 579.40 W/m^2, and 270.267 W/m^2, with a total solar energy of 16.40 MJ/m^2.

Detailed parameters results are shown in figure 5. Throughout the five-day testing, ambient temperature showed a similar trend as solar radiation, where temperatures increased during the first half of the day and decreased in the afternoon. The first day's minimum, maximum, and average temperatures were 29.69°C, 35.87°C, and 32.59°C, respectively. These numbers remained the same for the experiment. The drying chamber's internal temperature was continuously impacted by sun radiation and the outside temperature during the daytime drying operation. The results were influenced by solar radiation and external air condition that were used further to warm the heated air inside the drying chamber. The flow of heated air slowed as solar radiation dropped, resulting in a drop in temperature inside the drying chamber. On the first day, in sunny conditions, the drying chamber's minimum, maximum, and average temperatures were 27.11°C, 37.71°C, and 32.13°C. According to these results, the drying chamber's temperature was continuously higher than the surrounding air's, with an average range of 5 - 7°C. This temperature difference provides enough thermal energy to power the drying operation during the day. Additionally, the drying chamber's maximum temperature stayed below 50°C, which is appropriate for drying coffee beans (see Figure 6).

The off-daylight conditions indicate the temperature and humidity within the drying chamber and the surrounding environment during the night time. On the first night, the average ambient temperature was 25.57°C, with an average environmental humidity of 19.8 g/kg while the average temperature and humidity within the drying chamber were 25.69°C and 15.8 g/kg.

On the fourth night, the average ambient temperature was 25.86°C, with an average environmental humidity of 20.1 g/kg. The average temperature and humidity within the drying chamber were 26.50°C and 13 g/kg. These findings indicate variations in temperature and humidity within the drying chamber compared to the ambient temperature and humidity. The result shows the difference of 1°C variation in temperature between the internal and external condition of the drying chamber as shown in Figure 7. The temperature change is too small to drive the drying process. The difference between the humidity within the drying chamber and the outside air is between 19 and 35 %. The condition will speed up the drying process even when there is no sunlight at night. The coffee bean drying process occurs continuously 24 hours during five days, (see Figure 8). The results illustrate drying under both sunshine and non-sunshine conditions. On the first day under sunshine conditions, the initial weight loss of the coffee beans is faster due to the presence of free surface moisture.

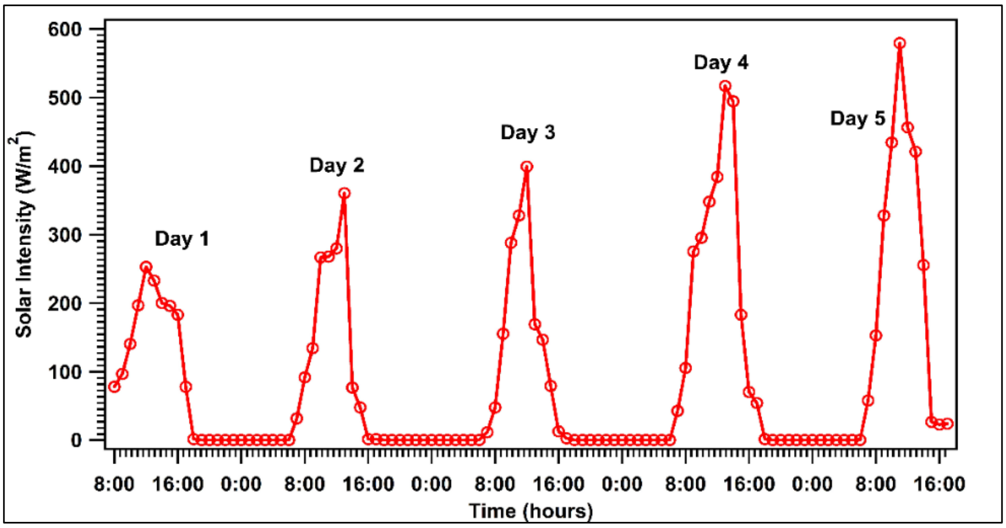

Fig. 5 - Example graph result shows variation of solar radiation during five days test. The parameter values significantly increase when daylight while off in night-time.

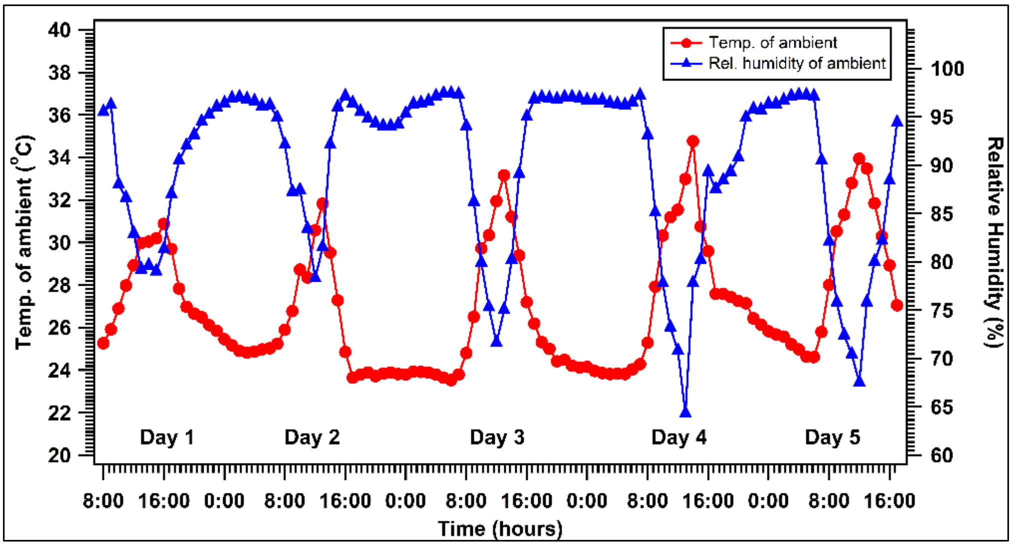

Fig. 6 - Variation of the ambient temperature condition (°C) with red-dots line and percentage of relative humidity in five days test with blue-triangles line.

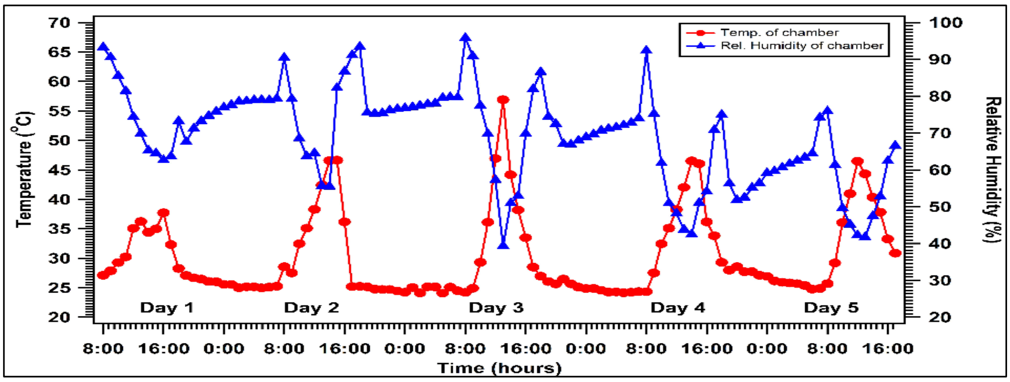

Fig. 7 - Variation of temperature and relative humidity of drying chamber. The blue line is the temporal graph of relative humidity percentage while red line is the temporal graph for the temperature process.

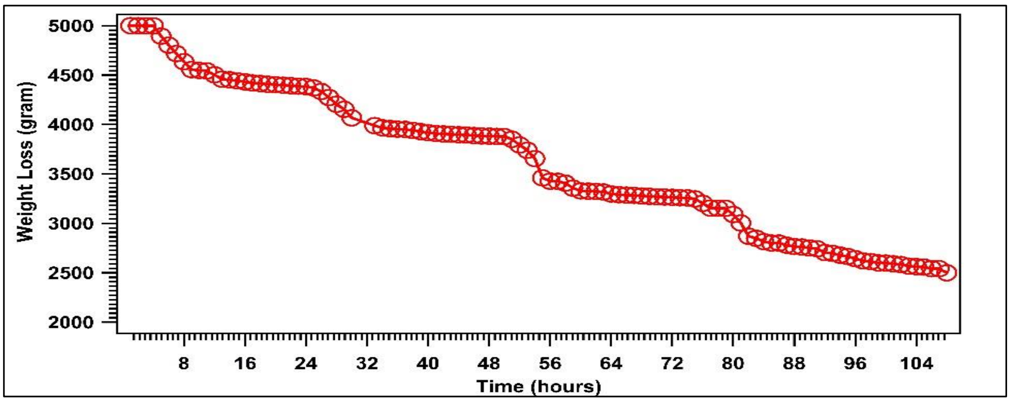

Fig. 8 - The weight loss in gram of coffee beans during solar and desiccant drying along five days. The initial weight is 5000 gram and significantly change to be 2500 gram along dry processing.

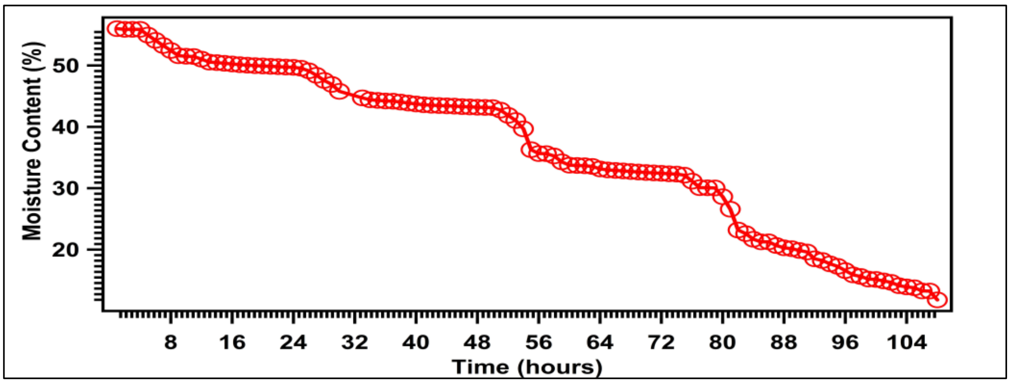

Fig. 9 - Variation of the moisture content with drying time for coffee bean along hour process. The moisture content significantly changes below 20% in after dry processing.

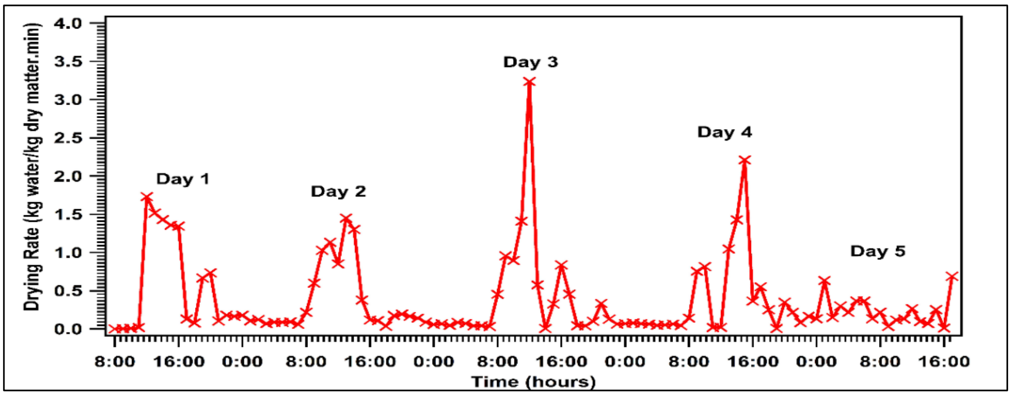

Fig. 10 Temporal variation of drying rate for coffee bean in five days. The graph shows that the highest value can be found in the third day with drying rate value ~3.5 while the lowest value in the fifth day with value < 1.0.

The weight loss is approximately 456.84 grams. Under non-sunshine conditions, the weight loss is about 119.24 grams when a molecular sieve is used. On the second day, under sunshine conditions, the weight loss of the coffee beans is around 420.07 grams. Under non-sunshine conditions, using a molecular sieve, the weight loss is about 62.21 grams. On the third day, under sunshine conditions, the weight loss of the coffee beans was approximately 524.49 grams. Under non-sunshine conditions, using a molecular sieve, the weight loss is about 66.93 grams. On the fourth day, under sunshine conditions, the weight loss of the coffee beans is about 447.75 grams.

Under non-sunshine conditions with a molecular sieve, the weight loss is about 187 grams. Finally, the weight loss of the coffee beans is around 100.02 grams after five days. The variations in the weight loss of the coffee beans can be connected to the varying intensities of solar radiation received by the solar collector. During the nighttime, the reduction in coffee bean weight is attributed to the desiccant material's ability to absorb moisture as a dehumidifier. The drying tests demonstrate the desiccant that can absorb moisture from the drying chamber, thereby reducing the humidity and water content of the beans as decreased mass. The testing concludes when the mass of the coffee beans reaches 2500.21 grams, corresponding to a coffee bean moisture content of 12%. An absence of conventional drying processes can be only operated during the daytime. The variation of moisture content versus time is shown in Figure 9. In the first daytime, the moisture content decreases rapidly from 56% to 51.46%, and on the first nighttime, it decreases from 51.03% to 49.70%. On the second daytime, it drops from 49.55% to 44.18%; on the second nighttime, it decreases from 44.03% to 43.14% as shown in Fig. 8. On the third daytime, it decreases from 42.73% to 33.70%; on the third nighttime, it drops from 33.66% to 32.29%.

On the fourth daytime, it decreases from 32.11% to 21.26%; on the fourth nighttime, it decreases from 21.25% to 15.62%. On the fifth daytime, it decreases from 15.19% to 11.80%. The high drying rate period and the dropping rate period are two segments of the drying process. The phase with the highest drying rate is the first few hours of the first day. This is due to the coffee beans' surface having a high moisture content as shown in Fig. 9. After this time, the drying rate will slow down as the moisture in the coffee beans (below the surface) diffuses to the surface over time. The graphic unequivocally demonstrates that the drying process occurs at night, even without sunlight. The drying rate curve for coffee bean drying with the use of a desiccant integrated with a solar collector is shown in Figure10.

The solar intensity conditions on the first and second days resulted in a lower drying rate than the third day. The findings indicate that drying happens at a decreasing rate, starting with a significant decrease in moisture content and tapering down on the fifth day. The significant change was caused by product shrinkage that may has a function as a barrier to moisture flow, and drying ultimately happens due to moisture diffusion within the product. As temperature is a critical component in influencing the quality of the dried product, slower drying rates result in better product quality. Misha et al., (2016) also found similar condition using solar-assisted to produce the oil palm. With 12.7% moisture content, the subsequent phase encompassed a laboratory assessment to elucidate the inherent attributes of the desiccated coffee beans as shown in Figure 10. Besides the reduced drying time, continuous drying characteristics exhibit higher values than conventional drying, particularly in protein composition. Furthermore, the experimental results successfully show that a solar dryer efficiently gained the quality of dried coffee beans by sustaining process during low or off-sunlight.

The solid dehumidification and sun dryer can be operated together and simultaneously and provide the coffee beans quality with easily absorb moisture at night. The air humidity difference between the drying chamber and the surrounding environment drops by 17% while the air temperature inside the drying chamber remains mostly constant during the off-sunlight drying procedure. Future study can be improved with multidisciplinary aspects such as a neural network analysis for longer days processing (Muksin et al., 2022; Simanjuntak et al., 2023), vulnerability environment to measure the risk from solar activities and impacts from climate and weather (Lubis et al., 2024; Asnawi et al., 2022, 2024) and public perception for agriculture engineering with sustainable energy.

4. Conclusions

The experimental results demonstrate that a solar dryer integrated with a solid dehumidification molecular sieve as a desiccant indicates the ability to sustain the drying process without sunlight and effectively preserve the quality of the dried coffee beans. Solar intensity affects the drying duration, particularly during daylight hours. The solar dryer integrated with solid dehumidification achieves a 108-hour drying duration to reach a moisture content of 12.7%. This drying process holds significant promise during periods of low solar intensity, as solid dehumidification during nighttime facilitates moisture absorption from the coffee beans. During the off-sunlight drying process, the air humidity differential between the drying chamber and the ambient environment reaches a 17% reduction, accompanied by a relatively consistent air temperature within the drying chamber. Moreover, the regenerative capability of the molecular sieve desiccant as solid dehumidification renders it suitable for repeated process.

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