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Performance Evaluation of an Inflated Solar Dryer Integrated with Phase Change Materials for Enhanced Drying of Cherry Coffee

Yeni Eliza Maryana[1,2], Daniel Saputra[3*], Gatot Priyanto[4], Kiki Yuliati[4]

[1] Doctoral Program of Agricultural Sciences, Faculty of Agriculture, Sriwijaya University, Palembang 30139, Indonesia
[2] South Sumatra Agricultural Instrument Standardization Center, South Sumatera 30135, Indonesia
[3] Department of Agricultural Engineering, Faculty of Agriculture, Sriwijaya University, Indralaya 30662, Indonesia
[4] Department of Agricultural Technology, Faculty of Agriculture, Sriwijaya University, Indralaya 30662, Indonesia

Corresponding Author Email: drdsaputra@unsri.ac.id

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ABSTRACT

The performance of an inflated solar dryer (ISD) integrated with solar air collectors and phase change materials (PCMs) was investigated for the purpose of optimising cherry coffee drying. Experimental trials were conducted to evaluate the efficacy of the dryer with and without the incorporation of PCM. Results indicated that the integration of waste cooking oil as PCM significantly enhanced the drying rate and overall efficiency of the ISD compared to its non-PCM counterpart. Quality assessments revealed that the PCM-based dryer effectively preserved the characteristics of green coffee beans, thereby mitigating quality degradation during the drying process. These findings suggest that the incorporation of PCMs within ISD systems presents a viable alternative for coffee bean drying, particularly in remote regions where climatic conditions are inconsistent and unpredictable. Further research is warranted to explore the long-term viability and scalability of this technology, which holds promise for improving agricultural practices in areas reliant on solar energy for drying processes.

1. INTRODUCTION

The drying industry uses a lot of energy. Solar energy can decrease the sector's energy consumption [1]. Solar energy is a valuable alternative energy supply favoured above other energy sources due to its abundance, limitlessness, and lack of [2-4]. Solar drying could be an alternative to industrial drying techniques [5, 6].

In most developing nations, the conventional technique for preserving agricultural products, including coffee, is open-air sun drying. However, this procedure has challenges with dirt, insects, rain, and dust contamination [7, 8]. To overcome these shortcomings, a variety of solar dryers have been produced that operate by trapping sunlight via a solar collector and connecting it to a dryer box or by setting it in a place that looks like a greenhouse and is covered in plastic or glass [9, 10]. The return on investment for this product is between 0.54 and 4.69 years, and it is designed in an environmentally friendly manner. This solar dryer is quite affordable to construct [11, 12]. When coffee is dried using a hybrid dryer rather than a traditional sun dryer, the highest protein content coffee is obtained [9]. The drying air temperature in a solar dryer can range from 37 to 45 degrees Celsius, which is optimal for drying coffee and results in the best coffee flavour compared to other drying techniques [13].

However, the solar dryer depends on the amount of sunlight and the duration of exposure. To overcome this limitation, researchers have developed a solar dryer that uses both latently and sensitively stored energy, allowing for longer drying times and fewer temperature fluctuations during the drying process [14]. The use of PCMs in drying methods, especially sun drying mechanisms, has received a lot of publicity because of its capacity to improve heat efficiency while still maintaining steady drying temperatures. In order to maximize drying processes, PCMs—materials that absorb and release heat energy during phase transitions, usually between solid and liquid states—can be strategically employed [15, 16]. PCM integration can reduce drying time by 40–60% compared to using without PCM [17-19].

The drying process of coffee beans can be done with various techniques, including using an inflated solar dryer. Armah et al. [20] found various products can be dried using ISD, a tunnel-type solar dryer that uses less energy and dries products more quickly than conventional drying. Salvatierra-Rojas et al. [21] and Ntwali et al. [22] stated that ISD designs are simple and straightforward to operate, quick to maintain, and can be set up in a new place in about 30 minutes. However, research on drying coffee with a mobile inflated solar dyer and using phase change material from used cooking oil is still very rare. The limitation of existing solar dryers, even though they use energy storage devices, is that they are all non-mobile devices that require farmers to travel to their location. Consequently, many farmers, especially those in isolated areas, are reusing open solar dryers.

Furthermore, the application of these techniques can also enhance the value of the goods that have been dried. Even without sun energy, the device's photovoltaic collector charges the fan's battery and blows a long balloon. The product is positioned above the padding inside the long balloons, and the long balloons form a long semi-cylinder that gets dry from solar energy. The process is initiated with the support of solar energy that penetrates the long cylinders [20, 22]. The main objective of this current experimental work is to present a construction for an inflated solar dryer that uses cooking oil wax as phase-changing properties. The first research was done to evaluate the influence of PCM on ISD performance in a dryer system. This entailed evaluating the system under two distinct conditions: with and without PCM. The objective of this study was to study the dryer's performance with and without PCM.

2. METHODOLOGY

2.1 Time and study sites

This research was carried out from April to December 2023. An indirect solar dryer was designed, installed, and evaluated at the South Sumatra Agricultural Instrument Standardization Centre, South Sumatra Province, Indonesia. The quality of green bean coffee was analyzed at the Indonesian Coffee and Cocoa Research Institute, Jember, East Java, Indonesia.

2.2 Design of inflated solar dryer

The inflated solar dryer has two main parts: the solar air collectors (internal and external) and the dryer tunnel (Figure 1).

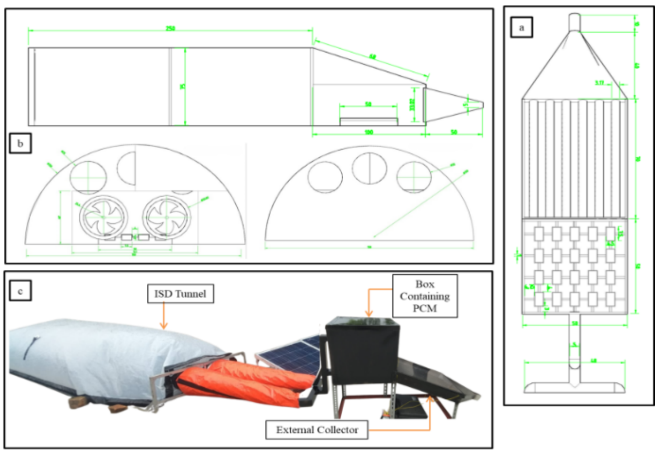

Figure 1. Design ISD (a) External solar air collector, (b) ISD tunnel, (c) General view of the solar dryer

a) Solar air collector

- External solar air collector

The external solar collectors have been designed as flat collectors with 0.7 m long and 0.5 m wide dimensions. Several components make up the structure of the solar collector: 1) the cover of the collector is made of acrylic glass with an inclination of 25 and is used to retain the heat that has been captured by the absorber plate so that it does not release it into the environment; 2) the solar collector comprises an absorbent plate made from wave stainless steel with a width of 0.5 mm, which has been painted in black. The wave plate is positioned between the glass cover and the absorber plate under the glass cover; 3) the insulation is 9 mm thick and is installed to cover the collection wall; 4) the collector outlet is connected to a 50 cm × 50 cm box consisting of 20 aluminium tubes containing PCM.

- Internal solar collector

The internal solar collector is placed on the front of the ISD. This collector is designed to measure 50 cm × 50 cm and is made of aluminium. The components of the internal collector are: 1) a collector cover made of acrylic with a 9℃ blending of the collector surface and 2) four squirrel tubes containing PCM whose surface is painted black; 3) insulation with a thickness of 9 mm mounted to cover the collection wall.

b) ISD tunnel

The designed 3.5-meter ISD dryer tunnel is made of PVC plastic for the base, and transparent UV plastic on the top serves as a cover. A waterproof zip connects both of these plastics. On the front of the ISD, two holes measuring 33.02 cm enter the airflow from the solar collector, and at the back, there are three exhaust holes of 25 cm each.

2.3 Experimental procedure

a) Drying coffee bean without PCM

The inflated solar dryer is spread out on the drying floor based on its length. The zips down the length of the device were opened, and 50 kg of coffee beans were loaded and placed on the dryer's base, which had a thickness of 2-3 cm. Sixteen k-type thermocouples attached to data loggers were installed in various positions to record temperature in accordance with the experimental design. After installing the thermocouple, the zip was closed. Two 12V fans were fitted using a collapsible aluminum bar frame. The black and translucent plastic sheets are linked to the ventilators using ropes. To maximize sunlight gathering, two solar panels (100 W each) were installed on aluminum rods facing north-south at a 45° angle. A solar battery was installed near the panels and connected to the solar panels and ventilator via a charge controller to receive charging during sunny days and vice versa at night or in bad weather. A black-painted flat plate collector is put in front of the ISD and connected with a pipe. Once the device was configured, the fan was turned on, and the drying process without PCM began. The trials lasted from morning to evening, and the drying procedure finished when the grain's moisture content reached the acceptable level of 12.5%wb. Moisture levels were determined at the beginning of the drying experiment and maintained at regular and consistent intervals until the end.

b) Drying coffee bean with PCM

ISDs, sixteen k-type thermocouples, fans, solar panels, solar batteries, and flat plate collectors were installed, the same as when drying without PCMs. The difference in installation is the inclusion of tubes containing PCM into the ISD drying chamber and flat plate collectors. This study uses PCM derived from cooking oil wax, which is put into a tube placed in the collector, which is integrated with a solar collector.

A 50-kilogram bag of coffee cherries was sourced from the farmers and placed into the ISD tunnel. The cherries were expanded into a 2–3 cm thick layer on the bottom. Trials were conducted from morning to evening, with the drying process concluding when the grain's moisture content reached the recommended level of 12.5%wb. Moisture level was determined at the initial stage of the drying experiment, at regular intervals, and consistent intervals until the final stage of the experiment.

The air entering the collector's flat plate generates additional solar energy through direct radiation through the transparent cover. This hot air then flows into the box that contains the PCM. This air generates extra heat through the energy released by the PCM. The air is then sucked by the two fans that are in front of the ISD and then entered into the ISD to dry the material. The function of the fans is to remove water vapour that evaporates from green beans and to help the airflow through the ISD tunnel. The air is discharged through the ISD outlet hole. Figure 2 displays the schematic design of the ISD setup.

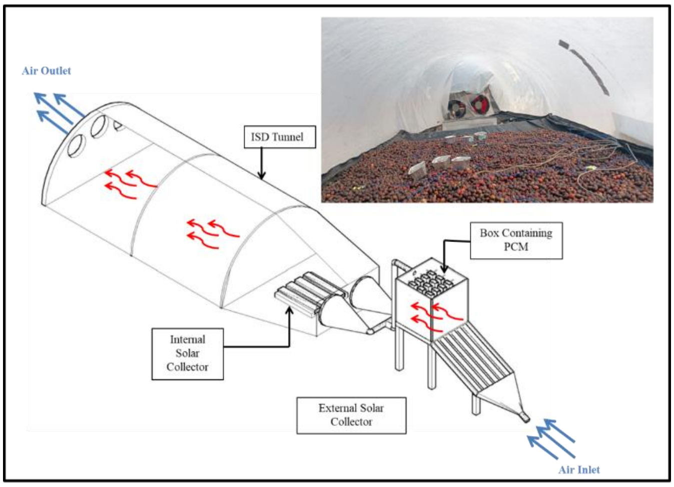

Figure 2. Schematic diagram of ISD system

Sixteen-type K thermocouples placed at various points (front of the collector, on the collector plate, air inlet ISD, air outlet ISD, inside ISD) to determine the temperature at each location. During the drying process, each of the sixteen thermocouples was attached to a data logger that was connected to a computer to record continuous temperature readings every 30 minutes. Solar energy in the area was quantified using a pyranometer. A hygrometer (HTC-1) was used to regularly monitor the ambient air's relative humidity and the drying chamber's interior with an accuracy of ±0.05%. A data logger (TASI model TA612C) recorded all climatic and measured parameters. An anemometer (Benetech model GM816 with an accuracy of ± 0.05 m/s) was used to record the airspeed at the outlet of the ISD during the experiments. Solar radiation and temperature were recorded every 30 minutes. The mass reduction of coffee green beans during drying is done every 4 to 5 hours.

2.4 Performance evaluation

The ISD's evaluation was monitored using dryer evaluation indices such as drying performance, colour change, and green beginning quality.

a) Drying performance of inflated solar dryer

The drying performance of the ISD was evaluated using and without PCM. The developed ISD was tested over 6 hours from 9 am to 6 pm. Performance evaluation of the inflated solar dryer was monitored using dryer performance parameters: drying efficiency, drying rate, temperature, and coffee cherry moisture content. The drying rate of the green began sample is a function of the initial moisture content and the air temperature. Drying efficiency is the total energy supplied to the ISD and the total energy used by the ISD to receive the desired moisture from the coffee cherries. The drying efficiency, was measured using Eq. (1), the drying rate was measured using Eq. (2), and the coffee cherry moisture content was measured using Eq. (3):

$$\eta = \frac{WLg}{E_t} \tag{1}$$

where, η=Drying efficiency; W=The weight of water evaporated, kg; Lg=The latent heat of evaporation of water, MJ kg^{-1}; Et=Total energy consumption.

$$Et = \frac{Rs \times A \times t}{10^6}$$

where, E_t=Energy consumption, MJ; Rs=Solar radiation, W m^{-2}; A=Drying area of SB dryer, m^2; t=Time required for drying, s.

$$DR = \frac{M_i - M_f}{DT} \tag{2}$$

where, DR=Drying rate, Percentage of moisture content per hr; M_i=Percentage of initial moisture content of cherry on wet basis; M_f=Percentage of final moisture content of cherry on wet basis; DT=Drying time, hr.

$$M_w = \frac{M_p(M_i - M_f)}{(100 - M_f)} \tag{3}$$

where, M_W=The mass of water removed from the cherry, kg; M_p=The initial mass of the cherry to be dried, kg; M_i=The initial moisture content of cherry on wet basis decimal; M_f=The final moisture content of green bean on a wet basis decimal.

b) Green bean color change

The coffee colour change is measured by assessing the colour of green coffee beans before and after drying with ISD and then comparing the colour change to that of conventional dried coffee beans. Measurement using CHN Colorimeter (CS-10; China) based on the CIE LAB method ΔE. Color parameters; L* (L*= 100 means white, L* = 0 means black), a* [redness (+) and greenness (-)], and b* [yellowness (+) and blueness (-)] were determined in the CIE L*a*b* space. Total colour differences (ΔE), chroma (C*), and hu (H*) were calculated using Eq. (3).

$$\Delta E *= \sqrt{(L_t - L^*)^2 + (a_t - a^*)^2 + (b_t - b^*)^2}$$

c) Green bean quality

SNI 01-2907-2008 was used to analyze the quality of the coffee green beans. A total of 300 grams of coffee beans were analyzed for their physical characteristics, including moisture content, dirt content, live insects, badly smeling substances and moulds. The following is a detailed explanation of each stage of the test.

- Moisture content testing

Testing the moisture content of coffee beans is done by drying coffee bean samples at 105°C for 16 hours under atmospheric pressure. This method is in accordance with the standards set out in SNI 01-2907-2008, which regulates the quality of coffee beans.

- Determination of coffee passing the sieve, defect value, and coffee bean impurities

The determination of coffee that passes the sieve as well as the value of defects and impurities of coffee beans is done by physical separation using a sieve that has round holes with a diameter of 6.5 mm and 3.5 mm. This process aims to separate coffee beans that meet the size standard and identify defective or dirty beans. After separation, the beans that passed the sieve were weighed to determine the percentage of beans that met the criteria. The defect value is calculated by counting the number of defective beans and comparing it to the total beans tested. Impurities are also weighed to determine the level of impurities in the sample.

- Live insect testing

Live insect testing is done visually when the sample packaging is opened. This test aims to ensure that the coffee beans are free from insect infestation. If no live insects are found, then the sample is declared free of insects. However, if insects are found, then the sample is declared contaminated.

- Determination of foul odour and moulds

Determination of foul odour and mould is done organoleptically, by smelling the aroma of the coffee beans in a container that is protected from the influence of the external environment. This procedure is important to detect any unwanted odours that may affect the quality of the coffee beans. If a foul or mouldy odour is detected, the sample is declared unfit. Conversely, if there is no suspicious odour, the sample is declared good.

2.5 Data analysis

Statistical analyses were conducted with three replicates for each measurement. Analysis of variance (ANOVA) was performed on treated coffee beans (GB ISD and GB Conv) to evaluate significant differences in color change using a randomized block design. The analysis was carried out using SPSS version 22 (IBM Corp., Armonk, NY, USA). Data are presented as mean ± standard deviation. An honest significant difference (HSD) test was applied at a significance level of $p < 0.05$ to compare mean scores between treatments.

3. RESULT AND DISCUSSION

3.1 Performance of inflated solar dryer

Temperature Distribution

The drying air temperature distribution in the ISD with PCM is relatively stable compared to without PCM (Figure 3). The average air temperature inside the PCM reaches 34.98℃ at the beginning of the drying process and remains relatively fixed at 33.28℃ until the end. The result is consistent with other studies that state that the energy stored in PCM helps stabilize the air temperature in the drying room to reach 40-45℃ [23]. PCMs are capable of storing thermal energy during periods of solar availability and releasing it when sunlight is insufficient, thereby ensuring a more consistent drying temperature and reducing drying times [15, 16, 24]. This is different from the air temperature without PCM, where the temperature reaches 30.13℃ at the beginning of the drying process and then decreases rapidly to 14.27℃ at the end as solar radiation decreases.

The ambient solar radiation temperature and the latent energy of the PCM strongly determined the air temperature inside the drying chamber. This is because the heated drying air inside the drying chamber is induced from the ambient air by the solar collector and heated by the solar rays; as the sunlight decreases, the ambient temperature and the temperature inside the drying chamber decrease.

The absence of PCM caused a noticeable decrease in the temperature curve's inclination between 3 and 6 pm. Coffee dried with PCM is not the same as this. In the course of drying, the PCM melts. The system's thermal load slowly reduces as the PCM melts, which causes the rate of temperature to increase. According to Duan et al. [25], the thermal conditions inside the drying chamber can affect how PCMs melt, enabling a more consistent temperature distribution.

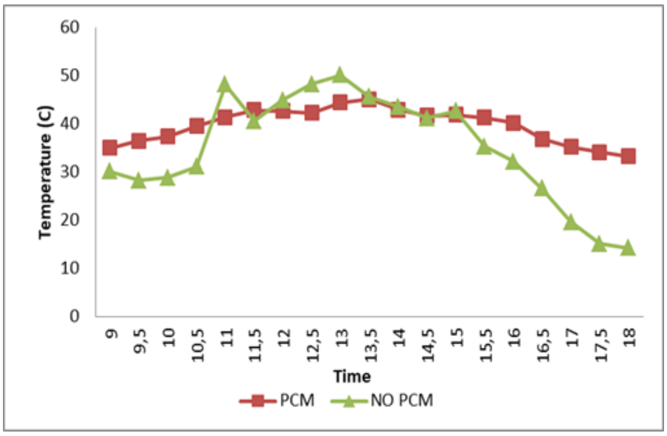

Figure 3. The daily temperature with and without PCM

During the coffee bean drying process, ambient air temperature, inlet air temperature, outlet air temperature, ISD chamber temperature, and ISD external temperatures fluctuate (Figure 4).

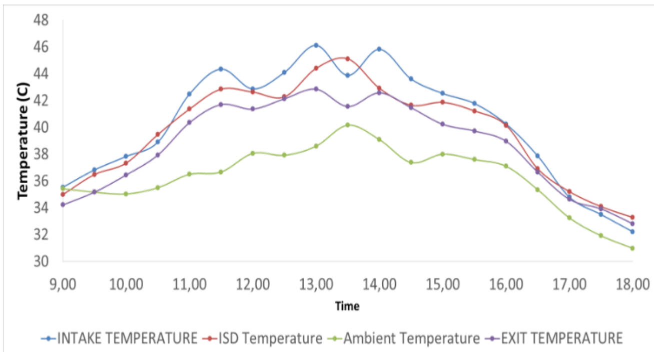

Figure 4. Average drying temperature at different points

The intake temperature, ambient air temperature, and average temperature in ISD from the beginning of the drying process continue to increase and reach a maximum temperature of 46.12. The air temperature entering from the collector to the ISD, the air temperature inside the ISD, and the air temperature exiting the dryer during the drying process are all higher than the outside air temperature.

The temperature of the air entering the ISD is higher than that of the outside air, indicating that the solar collector and the PCM used have been effective in raising the temperature of the incoming air. The temperature of the outside air that passes through the solar collector is then transferred to the ISD drying chamber. The heat intensity of the solar radiation absorbed in the collector can generate heat [26], and the heat transfer from the sun collector to the drying area may increase the air temperature to 45-60 [27]. The outside air flowing into the PCM box will met the wax used in palm oil. This condition provides additional energy to be introduced into the drying compartment [28].

Meanwhile, the air temperature entering the (40.28°C) is nearly equal to the air temperature inside the tunne (39.69°C). This indicates that drying has taken place. Drying occurs when air enters the ISD and sunlight penetrates the plastic ISD, raising the coffee temperature. With drying, the energy in the ISD drying tunnel will be able to dry the coffee cherry, lowering the air temperature coming out of the ISD.

Drying Performance

The drying performance of the inflated solar dryer (ISD) was evaluated with and without the use of phase change materials (PCM). Cherry coffee beans were dried from an initial moisture content of 28.28% and 29.30% to a final moisture content of 12.64% and 14.45%, respectively, for the trials with and without PCM. The total drying time required was 45 hours with PCM and 54 hours without PCM. The drying time was longer without PCM, indicating slower moisture removal. Furthermore, the drying efficiency was higher when PCM was used compared to when it was not used, as shown in Table 1.

Table 1. Performance ISD with and without PCM

	Initial Moisture Content (%)	Final Moisture Content (%)	Drying Time (hr)	Drying Rate (% mc/hr)	Drying Capacity (kg/batch)	Drying Efficiency (%)
PCM	28.28	12.64	45	0.35	50	45257.8
No PCM	29.30	14.45	54	0.276	47.7	41862.4

The drying rate of coffee beans with and without PCM reduces with time. At the end of the drying process, this number approaches zero, indicating a consistent pattern of moisture loss per unit of time. Figure 5 illustrates how the drying rate of PCM is higher than that of non-PCM from the beginning to the length of drying. The higher and more consistent temperature in the drying chamber while using PCM is thought to be the cause of this difference. Comparative studies have also demonstrated the benefits of employing solar dryers with PCMs as opposed to those without, emphasizing increases in energy efficiency and thermal performance [29].

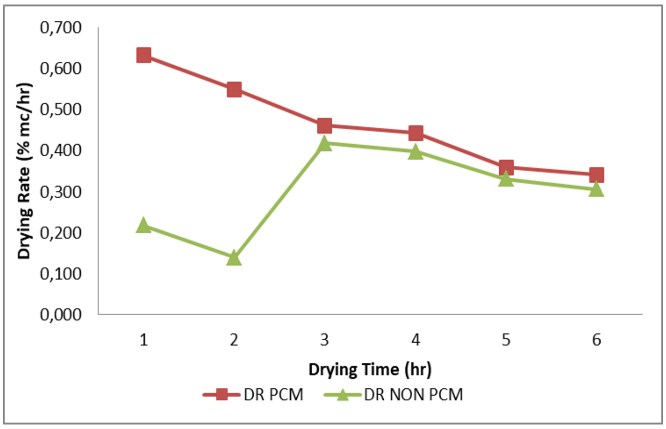

Figure 5. Drying rate of ISD with and without PCM

Another factor that influences the differences in the rate of water evaporation and drying efficiency between experiments is solar radiation and humidity content. Sunlight has an impact on drying as wel. Higher sun radiation intensity can reduce the drying moisture ratio and bulk coffee beans [27]. When drying with and without PCM, the average sun radiation is 323 W/m^2 and 270.3 W/m^2, respectively. The sample's initial moisture content significantly impacts how long it takes to dry. A shorter drying time is needed for a lower initial moisture content. It was discovered that using the generated PCM reduced the drying time compared to not using PCM. For example, Rulazi et al. [15] showed that combining a solar dryer with a thermal energy storage system greatly increased drying efficiency and shortened drying times for a variety of agricultural products. Several research findings also report that PCM can increase temperature, reducing drying time [30, 31].

Coffee beans dried without PCM showed reduced drying rates and efficiency compared to those dried with PCM. The temperature rises because of the heat generated by the PCM. The PCM from used palm oil has a latent heat of 43.68 kJ/kg for melting and a thermal conductivity of 0.154 W/mK [32]. The rate of water removal increases as the drying temperature rises [33]. Additionally, a high rate of water evaporation is followed by a high drying air temperature produced by the solar collector as a result of intense heat and mass transfer [30].

3.2 Green bean color change

The drying process is a factor that determines the value of the green coffee bean, one of which is its colour [34]. Green coffee beans' color, a crucial quality factor affecting how customers perceive them and price, is greatly impacted by the drying process. Green coffee beans change color as a result of several chemical and physical processes that take place during the drying process. The CIE L*a*b* color space is mostly used to quantify the color change; L* stands for lightness, a* stands for the red-green component, and b* stands for the yellow-blue component [35]. The test results of color changes in coffee with ISD and conventional are presented in Table 2.

Table 2. Color measurement results

Treatment	L*	a*	b*
GB ISD	26.42 ± 0.61^a	3.51 ± 0.06a	4.03 ± 0.73a
GB Conv	26.52 ± 0.39 a	5.72 ± 0.37b	5.21 ± 0.23ab
Cherry	30.78 ± 0.18 b	23.53 ± 0.72c	5.67 ± 0.64b

Table 2 illustrates how the sample's value is affected by the drying process. After the drying process, the L*a*b* value of dried cherry coffee decreases. Coffee cherries that were dried using an expanded sun dryer had the lowest value (3.51±0.06). Changes in drying time and temperature could cause the decreased reddish hull shift (a* value). The browning reaction does not last long when drying with ISD—a shorter drying period results in a discontinuous heating operation. When drying using ISD versus conventional methods, there is no statistically significant difference ($p<0.05$) in the measured L* and b* values. When compared to coffee beans before drying, it differs considerably. This is consistent with a study by Dong et al. [35], who discovered that green coffee beans' L* values tend to rise as they dry, signifying a change to a lighter hue. This phenomenon has been reported in research where drying coffee beans increased their L* values, indicating that the drying process makes the beans lighter than when they were first green. Likewise, the b* values, which indicate how yellow the beans are, also rise after drying, suggesting that dried beans are becoming more yellow in color.

After being dried using conventional and ISD methods, the average colour value of the coffee beans in the study was 16.34 E* and 20.57 ΔE*, respectivey (Figure 6). The drying procedure dramatically influences the overall colour variations of dried coffee beans; conventional drying has a lower ΔE value than ISD drying. Coffee beans dried using the traditional method have darker skin than coffee beans dried using ISD. This suggests that the developer colour shift is a result of the more prolonged exposure of the coffee beans to the drying process and the enzymatic browning reationship that occurs during conventional drying due to temperatures and drying time.

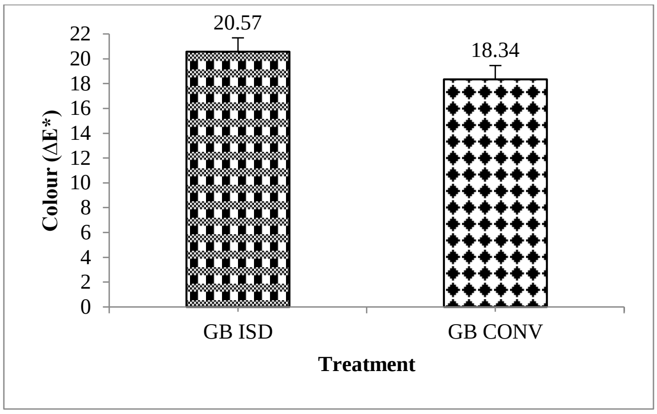

Figure 6. Color value of the coffee beans

The long drying time causes the degradation of the pigment, from the colour of the red pigment to the brown pigment. Longer drying times and conditions (such as UV light and oxygen) can trigger polyphenol oxidase (PPO) enzymes to oxidize CGA isomers. This process is recognized to produce polymers of ortho-kenne and brown pigments, which contribute to darker shadows in green beans, as shown by lower light (L*), redness (a*), and yelow (b*) values [36]. CGA isomers may undergo further degradation or transformation as temperatures rise to produce dark pigments [37].

3.3 Green bean quality

Table 3. Coffee bean quality measurement results

Chemical Content	Green Bean (Based on SNI)	Green Bean (Based on Research)
Live insects	0	0
Beans smell rotten and or stinking	0	0
Water content	Max. 12.5	10.89
Dirt content	Max. 0.5	0
Defective values	Max. 11	8.4
Passed the filter in diameter 6.5 mm, not passed filter diameter 3.5 mm (sieve No. 9)	Max. Pass 5	0.23

In this study, the quality of coffee is measured according to the national standard for green coffee applicable in Indonesia, SNI 01-2907-2008. The resuts of measurements of the physical quality of green coffee that began after drying with ISD are presented in Table 3.

ISD has good quality; it is shown that with all the parameters, no one excelled in the standard SNI boundary of green coffee beans. No live insects or green beans smelled rotten or scented on coffee drying with ISD, and no dirt. This is supposed because during the drying process, the coffee cherry is placed in transparent plastic to avoid dust contamination, dirt from the outside, and dangers from animals and insects. The ISD dryer provides an opportunity to improve dried product quality as the product drills under more hygienic environmental conditions. This dryer can reduce dryer time by more than 50% [38], thus not causing degradation [38, 39]. Long-term coffee drying tends to cause fungal green bean coffee [40].

In addition, the temperature used during the cherry drying process averagels 40℃, so it is assulmeld that the drying temperature is optimal and does not affect the damage to the green bean. The hotter the drying temperature, the greater the damage to cell membranes. Drying the coffee cherry at a temperature of 40℃ does not cause cell membrane change. At 50℃ drying heat, irregularities begin to occur in cell membranes, and when drying at 60℃, cells break, causing the formation of spacing between cells [41].

4. CONCLUSIONS

The inflated solar dryer has the potential to be applied as a solution to the problems faced by farmers who encounter limitations in time and drying facilities. The best treatment produced in this study is that the temperature generated is higher and remains stable until the afternoon, even though the sunlight is not optimal and the drying time required is shorter so that it does not affect the physical factors of coffee beans. This research is expected to provide new knowledge for farmers regarding the utilization of used cooking oil waste as a PCM in drying coffee beans.

Due to this research's limitations, future studies could focus on several topics, such as testing used cooking oil PCM in various weather seasons, designing latent heat storage systems for solar energy, and optimizing collector heaters using phase change materials.

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