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Energy and economic characterization of the traditional drying of cocoa beans in greenhouses

Caracterización energética y económica del secado tradicional de granos de cacao en marquesina

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ABSTRACT: Drying is a crucial step in cocoa production, for storing and reducing grain humidity. In Colombia, particularly in the Antioquia region, solar energy is used in simple structures called marquesinas. In this work, the authors characterized the process energetically by determining its specific energy consumption $(SEC, 27793.9kJ/kg)$, the thermal efficiency of the system $(\eta, 12.94\%)$, and specific cocoa drying process cost: 2.27 USD\$ $/\text{kg}_{\text{dry,cocoa}}$ $(aprox.10442COP\$/\text{kg}_{\text{cacaposseco}})$. At the end, with this information, is constructed grain mass loss curve versus time. The drying on the first day was faster than the following days. The main disadvantage of the greenhouse was that the beans gained moisture at night. For this reason, extra energy and time were necessary to remove the additional humidity acquired by the air condensing over the cocoa beans. This phenomenon decreased the thermal efficiency of the processes and increased its drying time.

RESUMEN: El secado es un paso de vital importancia en la producción de cacao, en el cual se reduce la humedad del grano para poder ser almacenado o tratado. En el departamento de Antioquia, en Colombia, el proceso se realiza aprovechando la energía solar en estructuras sencillas conocidas como marquesinas. En este trabajo, se caracterizó el proceso energéticamente determinando el consumo específico de energía $(SEC, 27793.9kJ/kg)$, la eficiencia térmica del sistema $(\eta, 12.94\%)$, y los costos específicos del proceso de secado de cacao 2.27 USD\$ $/\text{kg}_{\text{dry,cocoa}}$ $(aprox.10442COP\$/\text{kg}_{\text{cacaposseco}})$. Finalmente, se construyó la curva de pérdida de masa de los granos con respecto al tiempo. Se destaca que el secado en el primer día fue más rápido. La principal desventaja de la marquesina se encuentra en que los granos ganaron humedad durante la noche. Por esto, se empleó al día siguiente energía y tiempo adicional para remover esta agua ganada por condensación sobre los granos de cacao. Este fenómeno disminuyó la eficiencia térmica y aumentó el tiempo de secado.

1. Introduction

Cocoa drying is the post-fermentation process to reduce the moisture content of the cocoa bean from $\sim 60\%$ to approximately $\sim 7\%$. This postharvest process aims to prevent cocoa deterioration by avoiding mold formation. In this way, different production processes can treat the product after it is stored. Additionally, the drying phase is essential, and is a key determining unit operation in cocoa quality, because we find several properties of the grain that evaluate its quality, such as acidity and astringency

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[1, 2].

Currently, in many cocoa-producing countries such as Colombia, the process is carried out by hand, exposing the beans directly to solar radiation. In this technique, the grains are arranged or spread on a surface where solar energy is received, and a farmer manually mixes and turns the grains to ensure uniform drying. Although this method can meet the objective of drying, it is an inefficient procedure as it requires a long time for drying, is subject to weather conditions, requires constant labor to turn the grains, and affects the grain quality as it is exposed to environmental impurities during drying [3].

In the Antioquia region, cacao-producing farmers usually carry out their drying in the sun through *casa-elba*, a kind of dryer partially open receiving sun radiation, sometimes similar to open sun drying but with a metal roof in contact with sunlight and the structures known as greenhouses with a plastic UV protection from the sun (Figure 1) [4]. At casa-elba, the grains are spread horizontally on wooden structures raised from the ground about a meter high; some can be carts on rails that allow the movement of the structure. Greenhouses are wooden or metal structures with a roof as half a plastic cylinder, where an air inlet and an outlet are opened to guarantee the exit of humidity and prevent condensation; however, some growers located in Amalfi, Antioquia consider it a bad practice because heat is lost [5].

In the traditional cocoa drying process, the farmer evaluates the drying procedure by squeezing some beans. When the beans are crunchy (they break easily), this would indicate optimal drying. A final test involves splitting the grain and verifying that it acquires an entirely brown color. If it still has purple markings, time may be missing in the drying process, or the fermentation time has been exceeded [3, 6].

Some authors have investigated the drying of cocoa in greenhouses or *marquesinas*. In fact, researchers in Tabasco, Mexico [7], evaluated the efficiency and drying time of a tunnel-type solar dryer where they reduced drying from 3.5 days to 24 hours. In another study in Malaysia, [8] designed a greenhouse-type solar dryer and evaluated the quality of the dry grain, where they found that 20kg is the best choice to get better quality in a solar greenhouse dryer. Similar studies in Colombia. [9] and Cameroon [10] compared cocoa drying in a greenhouse-type structure to traditional drying in the sun. Researchers as well in Cameroon [4], reviewed the drying process using the mentioned techniques and a wood-fired oven, and they found that the best grain quality could be obtained with solar dryers: the oven one has less quality in flavor and scent. Similarly, other researchers [11] studied cacao drying in a kind of house structure, known as casa elba, and in a greenhouse known as marquesina, where they found better pH values in *marquesina* and oven than in *casa elba*.

In recent studies, in *Cameroon*, [12] conducted an experiment with five different types of greenhouses that used 3 covers to protect cocoa beans from the sun, using polyester, wool, and cotton: they found that the best cocoa quality comes from a greenhouse with a cotton cover, but it requires more than 40 hours drying. On the other hand, greenhouse-type solar dryers have been evaluated in other types of agricultural products, such as chili where they reduced drying time by more than 10 hours [13].
Under this scenario, in this work, the system's thermal efficiency, energy, and economic characterization of cocoa beans drying in a greenhouse-type structure in the Antioquia region is determined.

This research aims to compare the results of our investigation with those of other authors, in order to contribute to the state-of-the-art results regarding the energy performance and cost viability of these devices for growers in Colombia.

2. Materials and methods

The authors evaluated the drying process and its characterization according to the postharvest procedure commonly carried out in Colombian farms. A medium farm (<5 ha of cultivated cocoa) dedicated to cocoa production is the place of energy characterization. This farm is located in the municipality of Amalfi (Antioquia, Colombia), La Guayana village. The coordinates of the site are $6°54'33''\text{N}75°04'36''\text{W}$. It is located at 956 above sea level and has an average temperature of 21 °C . A greenhouse like the one in Figure 1 is where the process was implemented, located 1 m above the ground, where up to 200 kg of fermented cocoa could be dried. The structure had dimensions of 4 m long and 3 m wide.

One parameter to determine in this study is the specific energy consumption (SEC) in kJ/kg, which measures the amount of energy necessary for drying per kilogram of evaporated water. Equation 1 expresses the relationship to determine SEC, where Q_{net} (kJ) is the total energy delivered to the system to carry out the drying process; for the case analyzed, it corresponds to the energy absorbed by solar radiation in the greenhouse, and $\mathrm{m}_{\text{water}}$ (kg) is the mass of water evaporated during the drying process.

$$\mathrm{SEC} = \frac{\mathrm{Q}_{\text{net}}}{\mathrm{m}_{\text{water}}} \tag{1}$$

The difference between the mass of cocoa beans before

Figure 1 Greenhouse studied

starting the process m_i (kg) and the mass at the end of the drying process m_f(kg) represents the removed water mass, see Equation 2. The initial mass of the totality of fermented grains was $69.3\ \mathrm{kg}$ ($\mathrm{m_i} = 69.3\ \mathrm{kg}$).

$$\mathrm{m_{water}} = \mathrm{m_i} - \mathrm{m_f} \tag{2}$$

The authors collected data during the drying process, in 3 batches, 1 kg each, for fermented cocoa beans. Grain mounds were deposited in separate bins to avoid direct contact with the grain when recording mass measurements. Subsequently, the authors plotted a mass loss vs. drying time curve with the acquired values. Another parameter was the drying rate $\dot{\mathrm{m}}_{\mathrm{water}}\ (\mathrm{g/h})(\mathrm{g/h})$, identified in Equation 3.

$$\dot{\mathrm{m}}_{\mathrm{water}} = \frac{\mathrm{m_i} - \mathrm{m_f}}{\mathrm{t}} \tag{3}$$

Additionally, the moisture of the grain was determined in each hour of drying based on the initial moisture of the grain $(M_i, \%)$, from a mass balance in the drying process. Equation 4 , was used, which made it possible to predict grain moisture $(M, \%)$ at any moment in time, knowing the mass at that time. Building the grain moisture loss vs. drying time graph was possible with these determinations. This evaluation allowed estimating the average drying time associated with the traditional greenhouse process.

$$M = \left[1 - \left(m_i \frac{1 - M_i}{m_f}\right)\right] * 100\% \tag{4}$$

Figure 2 shows a balance of energy inputs and outputs in the greenhouse. Equation 5 relates the input and output energy terms associated with the traditional greenhouse drying process. Through the first law of thermodynamics analysis, the energy that enters the process was estimated, as well as the losses. Where $\mathrm{E_{IR}}(\mathrm{kJ})$ is the solar energy that reaches the surface or roof of the greenhouse during the entire drying process, $\mathrm{E_{far}}(\mathrm{kJ})$ is the work done by the farmer to mix the grains, $\mathrm{E_{eva}}(\mathrm{kJ})$ is the energy needed to evaporate the amount of water contained in the grain in such a way that the desired humidity is reached, $\mathrm{E_{WC}}(\mathrm{kJ})$ and $E_{DC}(\mathrm{kJ})$ refer to the energy that the mass of grains has associated with a temperature difference between the product and the environment at the beginning and end of the process, respectively; $E_{\mathrm{deg}}(\mathrm{kJ})$ is associated with the energy not used during the drying or degraded process, $\mathrm{E_{AI}}(\mathrm{kJ})$ is the energy of slow-moving air inside the greenhouse.

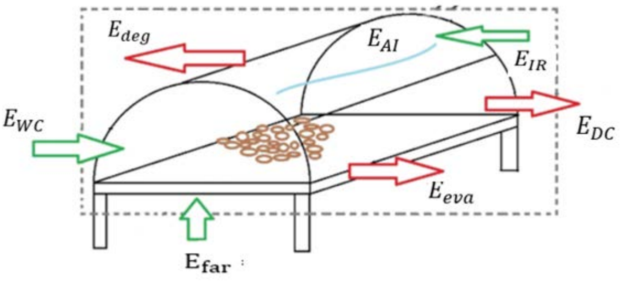


Figure 2 Greenhouse studied

$$E_{WC} + E_{far} + E_{IR} = E_{\mathrm{eva}} + E_{DC} + E_{AI} + E_{\mathrm{deg}} \tag{5}$$

Finally, the calculation of the thermal efficiency η, Equation (6), of the drying process was carried out considering the required input: the energy delivered to the system as the solar irradiation I (kW/m^2) that the surface of the greenhouse receives, and the desired output is the energy required to dry the cocoa beans. Drying energy refers to the sum of the energy needed to raise the temperature of the cocoa beans to the drying temperature and the energy needed to evaporate that amount of water from the beans.

$$\begin{aligned}\eta &= \frac{\text{drying energy}}{\text{solar energy provided}} \\ &= \mathrm{N} * \frac{(\mathrm{m_i} * \mathrm{Cp_{cocoa}} * (\mathrm{T_{sec}} - \mathrm{T_{amb}}))}{\mathrm{I} * \mathrm{A} * \mathrm{t} * \omega} + \\ &\quad \frac{(\mathrm{m_{water}} * \mathrm{h_{fg@\,T_{sec}}})}{\mathrm{I} * \mathrm{A} * \mathrm{t} * \omega}\end{aligned} \tag{6}$$

Where N refers to the number of days used in drying, $\mathrm{Cp_{cocoa}}\ (\mathrm{kJ/kg^\circ C})$ is the specific heat of the cocoa beans, $\mathrm{T_{sec}}\ (^\circ\mathrm{C})$ is the temperature that the beans reach inside the greenhouse, $\mathrm{T_{amb}}\ (^\circ\mathrm{C})$ is the ambient temperature of the site, $A(m^2)$ is the area on which solar radiation falls, $\mathrm{h_{fg}}(\mathrm{kJ/kg})$ is the enthalpy of vaporization of water at the drying temperature, t (s) is the drying time and ω is polyethylene transmission factor through plastic. The temperature of cocoa beans was measured as a function of time to determine the variable of interest, $\mathrm{T_{sec}}\ (^\circ\mathrm{C})$. The authors measured the temperature of the grains stored in the containers, and inside the greenhouse distributed at 9 different points. Other interesting variables measured were the ambient temperature $(\mathrm{T_{amb}}, ^\circ\mathrm{C})$ and the relative humidity inside the greenhouse e $(M_m, g/g)$, which allowed determining how much the temperature increased during drying, and the effectiveness of the drying process. If moisture accumulates inside the enclosure, it can then condense and affect the drying process.

For the measurement of solar radiation, a Kipp & Zonen model CM3 pyranometer with an accuracy of $\pm 25\ \mathrm{W/m^2}$ was used, reference temperature and relative humidity sensors AHT21 ASAIR with an accuracy of $\pm 0.3°\mathrm{C}$ and $\pm 2\%\mathrm{RH}$, respectively, located inside and outside the greenhouse. The sensors and the pyranometer were integrated into a data acquisition system (Datalogger) with a sampling frequency of 12 min. An infrared laser thermometer was used to measure the temperature of cocoa beans with an accuracy of 1.5 $°\mathrm{C}$. In evaluating mass loss in the mounds of cocoa beans, a digital scale of precision $\pm 0.1\ \mathrm{g}$ was used for a maximum capacity of 10 kg. Figure 1 illustrates the characterized greenhouse, showing the scattered grains and the 3 mounds of grain whose mass was monitored.

Another interesting variable in this study was the specific cost associated with the drying process per mass unit of dry beans $\left(\$\mathrm{COP}/\mathrm{kg}_{\text{dry cocoa}}, \$\mathrm{USD}/\mathrm{kg}_{\text{dry cocoa}}\right)$. For this, fermented grain cost (cost $_{\text{cocoa,ferm}}$, $\$\mathrm{COP}/\mathrm{kg}_{\text{dry,cocoa}}$) is $0.92\mathrm{USD}\$/\mathrm{kg}_{\text{dry,cocoa}}\ 1 \quad \left(4231\$\mathrm{COP}/\mathrm{kg}_{\text{dry,cocoa}}\right)$, cost of labor $\left(\mathrm{cost}_{lab},\ \mathrm{kg}_{\text{dry,cocoa}}\right)$ assuming that the business day is USD$11.18 (51416 $COP) and greenhouse investment cost (cost $_{\text{inve}}, \mathrm{kg}_{\mathrm{dry,cocoa}},$) with installation is 543.5 USD$(2,500,000\mathrm{COP})$. The drying cost was calculated according to Equation 7. This data was essential to assess the feasibility of using this type of device and compare it with similar ones. The production cost of dry cocoa per kg was calculated with the following Equation 7:

$$\mathrm{cost}_{\text{dry}} = \mathrm{cost}_{\text{cocoa,ferm}} + \mathrm{cost}_{\text{lab}} + \mathrm{cost}_{\text{inve}} \left(\frac{\$\,\mathrm{COP}}{\mathrm{kg}_{\text{dry,cocoa}}}\right) \tag{7}$$

3. Results and analysis

3.1 Drying curve

Figure 3 is divided into 4 graphs to compare the drying process each day and clarify the start drying and final drying moments. This shows the evolution of the average mass loss of the grain mounds in each hour, during the drying process during February 19, 20, 21, and 22 of 2022. For radiation values for those days, please see Figure 6.

According to Figure 3 and contrary to expectations, the mass loss did not consistently decrease throughout the drying process. The mass loss was not significant due to less solar radiation at the end of the day. However, the grains gained moisture at night, so the mass increased again. Therefore, authors estimated that the first two drying hours could remove the humidity accumulated during the previous night, i.e., six drying hours were invested in removing the moisture gained during the night. The authors got this value following drying processes during the first hours. Moisture gain during the day occurs because when solar radiation began to decrease, more or less after 3:30 P.M., the humid air inside the greenhouse began to cool, reversing the vapor phase changing from water that remained on plastic walls of the greenhouse and condensed directly on cocoa beans, generating an increase in mass to the beans, as observed in Figure 3, especially on days 2 and 3, ending the mass fraction around 56% (day 2), starting at almost 60% (day 3), ending at 48% (day 3) and starting at 52% (day 4).

Figure 3 shows that the drying was faster during the first day and slower on the consecutive days; this happens because the drying rate of the cocoa bean was greater when there had higher moisture contents, which occurred on the first day, when the cocoa beans had a lot of humidity around their body, especially on their surface [14]. Moisture displacement within the grains was governed by diffusion and capillarity but not for radiation, because this is a transport phenomenon, since they were not saturated with water. At the same time, for the second day of decreasing rate, moisture displacement could be attributed to flow due to shrinkage, pressure gradients, and gravity [15, 16].

When evaluating the drying rates on each day, values of 37.1, 14.3, 14.,2 and 12.1 g/h were calculated on drying days one, two, three and four, respectively, according to C.L. Hii *et al.* [17] Based on mass loss, the total drying time was 77 hours, during which the grains received significant solar energy for the first 32 h. Cocoa drying studies in greenhouse dryers, in Colombia reported a drying time of 3.5 days [6], in México 24 hours [7], in Cameroon 5 days [8], and in Trinidad and Tobago [9] 11 days; some of them with intermittent drying. According to this information, we can see that the traditional cocoa drying process can take almost 3.5 days of intermittent drying hours.

In the artisan process of producing cocoa beans, the person in charge of the process estimates its completion through a visual inspection analysis of the color, shape, and texture of beans. Figure 4 shows the grain images for each day of drying. On the first day (Figure 4a), the interior of the grain is observed to have a purple-pink color. Throughout the rest of the process, on day 2 (Figure 4b) and day 3 (Figure 4c), the color of the grain darkened until it reached an opaque brown coloration on day 4 (Figure 4d), chocolate color.

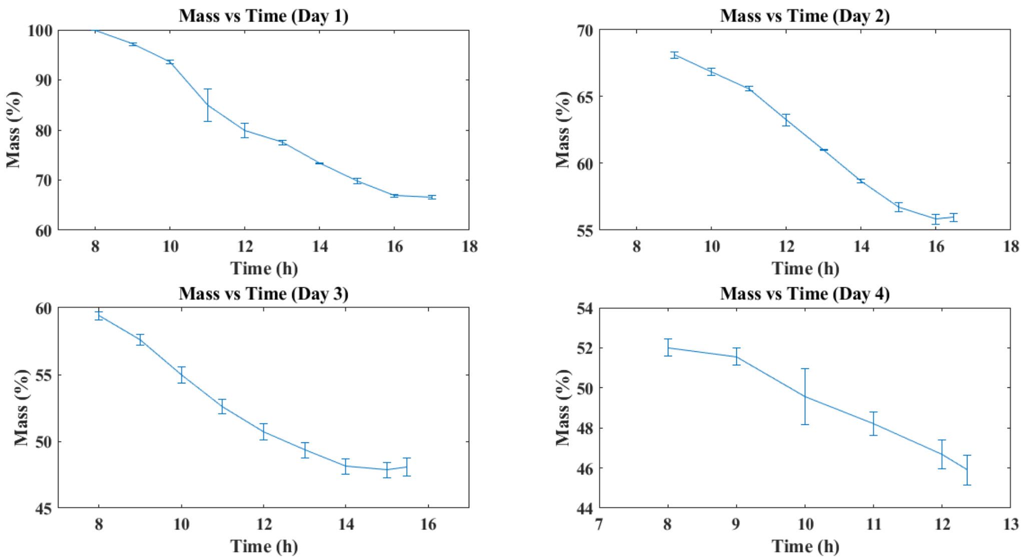
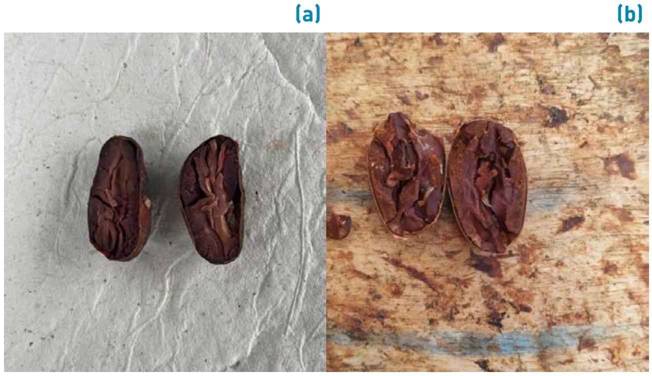


Figure 3 Grain mass loss as a function of time

(a) (b)



(c) (d)

Figure 4 a) day 1, b) day 2, C) day 3, d) day 4, Evolution of the physical characteristics in grain

3.2 Temperature

Figure 5 shows the ambient temperature of the area, the temperature inside the greenhouse, and the temperature of the grains during the four days of drying. During the experiment time, the temperatures inside the greenhouse, outside the greenhouse, and grain temperature obtained average values of $46.44 \pm 11.32°\mathrm{C}, 30.8 \pm 5.32°\mathrm{C}$, and $40.29 \pm 12.2°\mathrm{C}$, respectively, where the result of the temperature inside the greenhouse was the highest, making this hot air favor the drying of the cocoa beans, since it had low relative humidity, which promoted the evaporation of water from the surface of the cocoa beans into the air.

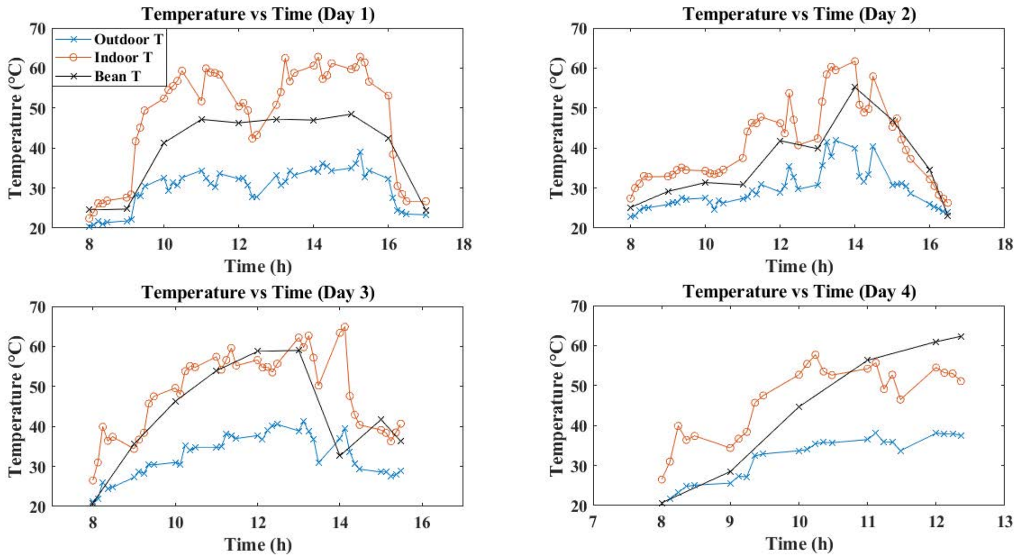


Figure 5 Temperature as a function of drying time

Greenhouse was a suitable structural assembly to increase the temperature since the temperature inside the greenhouse was higher than the ambient temperature at all times of solar radiation, finding temperature differences of up to 30 $^{\circ}\mathrm{C}$. As a result, in specific time intervals, the temperature of the cocoa beans rose to values above 60 $^{\circ}\mathrm{C}$. Although it may be an indicator of faster drying, some authors consider that exceeding this temperature in drying can affect the properties of the grain [[8],p.25].

3.3 Relative humidity and solar radiation

Figure 6 shows the relative humidity inside and outside the greenhouse and the intensity of solar radiation. The values obtained for the relative humidity inside the greenhouse, relative humidity outside the greenhouse and solar radiation were $51.61 \pm 16.3\%, 27.02 \pm 32\%$ and $539.8 \pm 476.6\,\mathrm{kJ/m^2}$, respectively [18].

Figure 7 shows the relative humidity data and specific humidity outside and inside the greenhouse. For the four drying days, the specific humidity inside the greenhouse was higher than the specific humidity outside. (dried). Specific humidity was obtained with two air characteristics inside and outside the greenhouse. These characteristics are saturation temperature and relative humidity, and with those values, using a psychometric chart, specific humidity can be obtained [19]. The saturated liquid state of the greenhouse environment was evident due to the drops of water that were perceived when entering it. Consequently, regarding cocoa bean drying, this saturated liquid state delays achieving the 7% moisture target, as these water droplets condense again on the cocoa bean surface. We saw water drops inside the greenhouse, because air is not flowing through open holes around the polyethylene plastic roof: they are partially open and during the night, the temperature is down, causing condensation.

3.4 Specific energy consumption

The solar energy received at the site for the four days of drying was estimated as $54071.2kJ/m^2$, performing a numerical integration of the radiation data collected by the pyranometer. Solar radiation hit the greenhouse plastic surface of Figure 1. This surface was estimated as a half-cylindrical cap with a diameter of 3 m and a height of 4 m, i.e., an area of $18.85m^2$. According to Eyco Laboratories [20], polyethylene has a transmission factor of 85% during operation. This factor multiplied by radiation is the solar energy provided. In this way, the total energy delivered to the system $\mathrm{Q_{net}} = 866335.75\,\mathrm{kJ}$ was calculated. During the analysis process, $\mathrm{m_{water}} = 31.17\,\mathrm{kg}$ was evaporated. Therefore, the SEC was $27793.9kJ/kg$, (for 69.3 kg of fermented cocoa mass); it is a value that is close to the range reported by S. F. Dina *et al.* [21] for cocoa drying by solar dryer integrated by desiccant absorber, adsorber, and simple dryer the specific energy was $13290kJ/kg$ moist, $18940kJ/kg$ moist and up to 60400 kJ/kg moist, respectively, for a load of 1 kg of cocoa beans.

3.5 Energy efficiency

During each day of drying, energy is required to raise the temperature of the grains from the ambient temperature, $\mathrm{T_{amb}} = 22.8^{\circ}\mathrm{C}$ (on average for the days studied) to the drying temperature, estimated as the average maximum

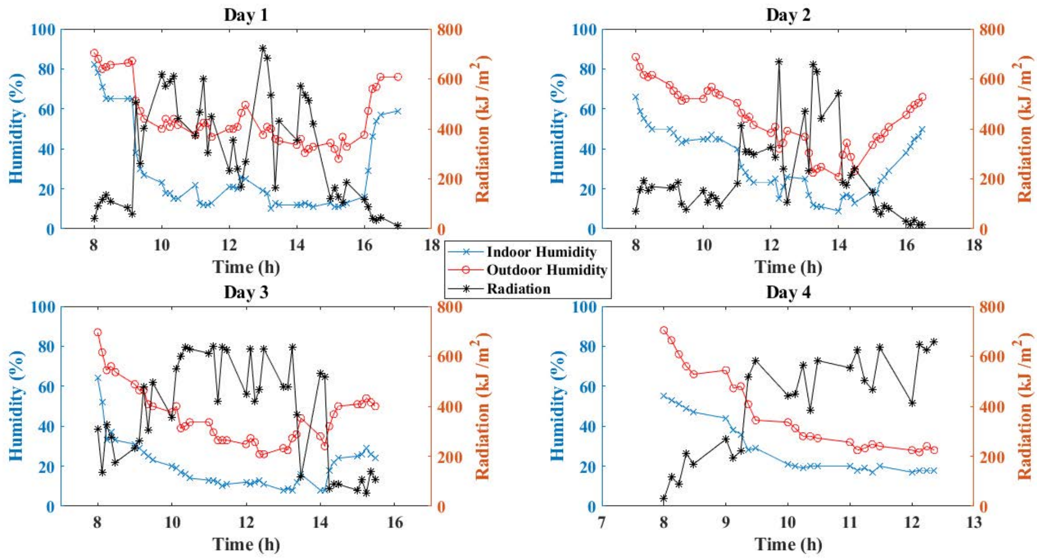


Figure 6 Relative humidity and radiation as a function of time

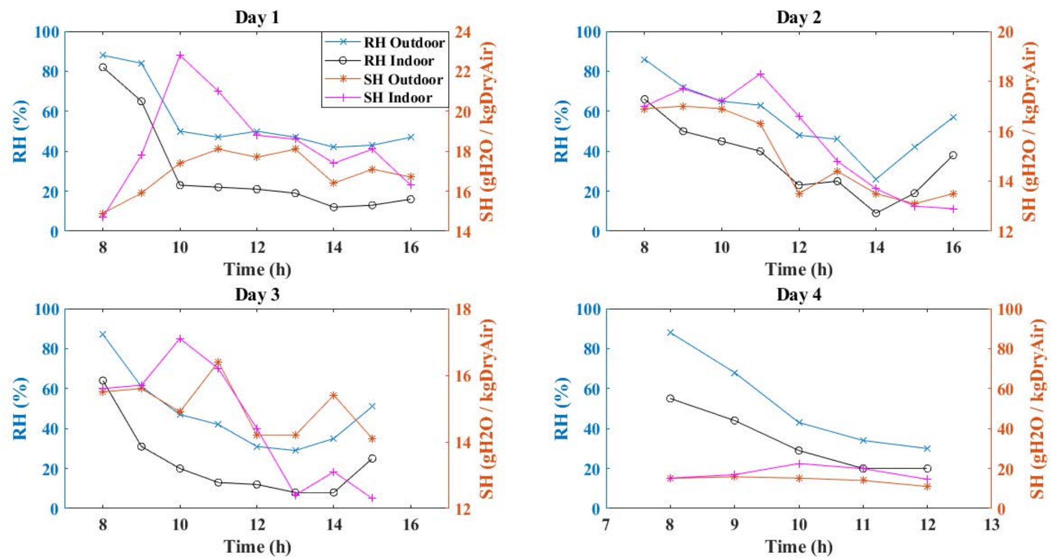


Figure 7 Relative humidity and specific humidity as a function of time

temperature in the four days, $\mathrm{T_{sec}} = 60 \pm 6.8°\mathrm{C}$. The authors assumed the value of the specific heat of cocoa beans as $\mathrm{Cp_{cocoa}} = 3.746\,\mathrm{kJ/kg°C}$ [[15, 22],p.1]. It is important to note that this energy expenditure occurred in the four days of drying: $\mathrm{Cp_{cocoa}} = 3.746\,\mathrm{kJ/kg°C}$ [15, 22].

It is important to note that this waste energy occurred during the four days of drying. During the night, the temperature of the grains dropped, and the next day, it was necessary to raise the temperature again. In this interval, the process required $38628.1kJ$ of energy to elevate the temperature beginning every day.

The second term in Equation 6 represents the energy required for drying and corresponds to the energy to evaporate the mass of water removed during drying, so the mass of evaporated water (m_{water}) was $31.17kg$. It was possible to estimate the enthalpy of vaporization of water at the drying temperature using water saturation tables, $\mathrm{h_{fg}@60°C} = 2357.7\,\mathrm{kJ/kg}$ [23]. Therefore, the energy needed in this water evaporation process was $73489.5kJ$. Thus, the total energy for drying was the sum of the energy required to evaporate water and raise the temperature of cocoa beans, $\mathrm{Q_{dry}} = 112117.7\,\mathrm{kJ}$.

Previously, the authors estimated solar radiation energy to $b_{be}Q_{\text{net}} = 866335.75\,\mathrm{kJ}$. During drying, farmers turn the grains over the wood to help with uniform drying.

Based on the mechanical work definition, the farmer's energy was evaluated throughout the process. This work energy comes from Equation 8, where the first term is the movement work to blend cocoa grains and the second term is the work related to a friction force.

$$W_{\text{far}} = W_{\text{mov}} + W_{fr} \tag{8}$$

Where:

$$\mathrm{W_{mov} = F_{mov} * d * n} \tag{9}$$

$$F_{\text{mov}} = m * a \tag{10}$$

$$W_{fr} = F_{fr} * d * n \tag{11}$$

The Equation 9 shows the work done by the cocoa farmer, where "d" is distance and "n" is cocoa mixed times. In Equation 10, F_{mov} is movement force, *m* is cocoa mass and *a* is gravity,"m" is an average mass during the drying process.

From Equation 11, F_{fr} is the friction force movement between beans and the *marquesina* wood. Moreover: the wood friction coefficient $\mu = 0.6, d = 1m$, and $n = 32$ is the total amount of times that the cocoa beans are mixed during drying each hour for the total drying time. Anyway, with that information, the authors calculated the farmer's energy throughout the process as 38.8 kJ. This is a negligible value compared to the solar energy received, so this value will not be considered in efficiency calculations.

The energy to dry cocoa and energy delivered to the system during drying, as you can see in Equation 6, are components to determine the thermal efficiency of the drying process in the greenhouse, and the quotient of these two quantities was $\eta = 11\%$. The estimated thermal efficiency for this case is only for 69.3 kg of the fermented cocoa beans dried in the greenhouse. However, the system had a maximum drying capacity of 200 kg of fermented grains, so the value of n can vary depending on the amount of dried mass and, obviously, weather conditions of the days the drying occurs.

A thermal efficiency (η) of 12.94% could be considered a low value; however, according to [24], a study of natural and convective solar cocoa bean dryers reported that due to low consumption of specific energy compared to other products and methods of air convection, they found the global thermal efficiency is in a range from 5% to 18 due to low consumption of specific energy compared to other products and methods of air convection [24].

Table 1 summarizes some of the most relevant parameters in the analysis of this work.

Table 1 Summary results

Parameter	Unit	Value
Solar energy received	kJ	866335.75
Energy for drying	kJ	112117
Specific energy consumption	kJ/kg	27793.9
Drying time	hour	77
Average drying rate	g/h	16
Thermal Efficiency	%	12.94
Drying cost (see 3.7)	USD/kg (COP/kg)	$2.27 ($10442)

3.6 System energy balance

Equation 5 established that the input´s energy system comes from solar radiation $(\mathrm{E_{IR}, kJ})$, energy by mechanical work of grain turning by the farmer, which is very small compared to the value of the total energy received by the greenhouse. Finally, upon entering the greenhouse, the energy from the cocoa beans is zero because the beans are at room temperature. In this way, $E_{IR} = Q_{\text{net}} = 866335.75\,\mathrm{kJ}$. Output energy term of balance is the energy to evaporate previously estimated water. With the energy associated with the cocoa mass at the exit of the drying process and calculated based on cocoa mass at the end of drying, the specific heat of the cocoa beans, the difference between the average bean temperature throughout the measurement (40.66 $^{\circ}\mathrm{C}$ was the average during the entire measurement) and the ambient temperature, we obtained $\mathrm{E}_{DC} = 389.39\,\mathrm{kJ}$. The $\mathrm{E_{AI}}$, which is the energy of the air circulating inside the greenhouse, was obtained by multiplying the mass of air that comes out of finding the volume of air in the greenhouse with air density, the specific heat of the air, and the difference in temperature between the outside and inside of the greenhouse, generating a $\mathrm{E_{AI}}$ of $212.74kJ$. In this way, from Equation 5, the energy or heat losses can be estimated as $\mathrm{E_{deg}} = 792244\,\mathrm{kJ}$. Figure 8 represents the Sankey diagram, and it illustrates the percentage energy distribution derived from the mass and energy balance of Equation 5.

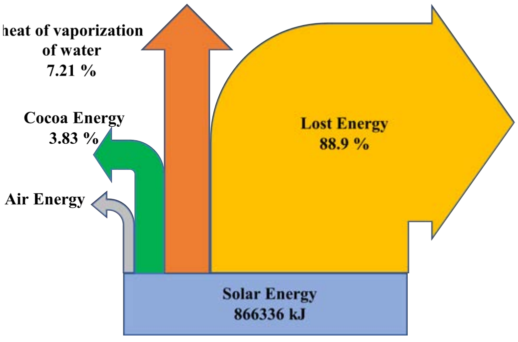


Figure 8 Sankey diagram of the greenhouse used in the traditional drying process

3.7 Cost of the drying process

The cost of fermented beans refers to the costs per operation of planting, maintaining, fertilizing, harvesting, and fermenting the cocoa bean in a medium-sized cocoa farm (< 5 ha), with all these activities located on the same farmland. If fermentation is done in a different location from the cultivation takes place, transportation costs must be considered. The development of these activities, from sowing to cocoa fermentation, costs USD $0.92 (4231 COP$) per fermented kg, according to a communication with Fedecacao (National Federation of Cocoa Growers, Colombia). In the measurements, the initial mass of fermented grains was 69.3 kg, and the final product of dry grains was 38.13 kg. From this relationship, a farmer can get 0.55 kg dried cocoa beans for each kilogram we ferment inside the *marquesina*. Consequently:

$$r=\frac{\text{mass in}}{\text{masa out}}=\frac{69.3\ \mathrm{kg}\ \text{wet cocoa}}{38,13\ \mathrm{kgcocoadried}}=1,817\frac{\mathrm{kg}\ \text{wet cocoa}}{\mathrm{kg}\ \text{cocoa dried}}$$

According to the fermented kg cocoa price, we have:

$$\text{Cocoa wet cost }=\frac{4231\ \text{COP}\ \$}{\text{Cocoa wet cost}}*1,817\frac{\mathrm{kg}\ \text{wet cocoa}}{\mathrm{kgdriedcocoa}}=7688\frac{\mathrm{COP}}{\mathrm{kgdried}\ \text{cocoa}}$$

$$\text{So, cost }_{\text{cocoa,ferm}}=1.656\frac{\text{USD }\$}{\mathrm{kg}_{\text{cocoa,dry}}}$$

The greenhouse investment cost, with a drying capacity of 200 kg and a surface area of 12 m^2 was 543.47 $USD ($\sim$ 2,500,000 CCOP$, TRM of 4600 COP$ /USD$, date $06/10/2022$) [25]. The authors estimated that the useful life of this structure is four years. On average, two dryings are carried out per month; therefore, 96 drying cycles are reached during the useful life, which means a cost of 6.85 USD$/cycle (31510 COP$/cycle), which is the discrimination of the total value of the greenhouse in the 96 cycles. Assuming that each work cycle is developed, and that 38.13 kg of dry grain are obtained, the authors calculated the investment cost as:

$$\text{cost }_{\text{inve}}=0.68\mathrm{USD}\$/\mathrm{kg}_{\text{dry.cocoa}}\ (3128\mathrm{COP}\$\ \mathrm{kg}_{\text{dry.cocoa}}).$$

The greenhouse operating system is easy; nevertheless, it requires the farmer to sweep or mix the grains every hour to seek uniform drying. The working day in Colombia for the year 2022 was 10.96 USD$, including all legal benefits (around 50416 COP$). Considering a total of 32 h of drying, and a mixing time close to 10 min each hour, approximately 5.33 h of labor are required, with a cost of 7.25 USD$(33350COP)$. This led to a labor cost for drying.

Table 2 Summary results

Parameter	Unit	Value
$\mathrm{cost}_{\text{cocoa,ferm}}$	$\frac{\text{USD}\$}{\mathrm{kg}_{\text{dry.cocoa}}}$	1.656
$\mathrm{cost}_{\text{inve}}$	$\frac{\text{USD}\$}{\mathrm{kg}_{\text{dry,cocoa}}}$	0.68
$\mathrm{cost}_{\text{lab}}$	$\frac{\text{USD}\$}{\mathrm{kg}_{\text{dry,cocoa}}}$	0.16
$\mathrm{cost}_{\text{dry}}$	$\frac{\text{USD}\$}{\mathrm{kg}_{\text{dry,cocoa}}}$	2.27

$$\mathrm{cost}_{\text{ab}}=0.16\mathrm{USD}\$/\mathrm{kg}_{\text{dry,cocoa}}\ (736\ \text{COP}\ \$/\mathrm{kg}_{\text{dry,cocoa,}})$$

Finally, adding the costs of fermented grain (cost $_{\text{cocoa,ferm}}$), investment costs ($\mathrm{cost}_{\text{inve}}$), and labor costs ($\mathrm{cost}_{\text{lab}}$), a specific drying cost is:

$$\text{Cost }_{dry}=2.27\mathrm{USD}\$/\mathrm{kg}_{\text{dry.cocoa}}\ (10442\ \text{COP}\ \$/\mathrm{kg}_{\text{dry,cocoa}})$$

for each kg of dry grain obtained during the cocoa benefit process.
Table 2 shows the final cost for every item required to calculate cocoa drying cost per kilogram cocoa dried.

In other studies, with similar calculations, investigators found that in El Empalme Cantón region, La Caraca, Ecuador, a project was implemented to modernize fermentation compared with the traditional fermentation process. The referred authors found that the annual variable and fixed costs incurred by fermentation per 100 quintals (10000 kg), where the variable costs considered were labor, materials, and inputs, while the fixed costs considered correspond to electricity and transportation [3]. In Brazil, they indicated in a technical-economic analysis of coffee processing (a process similar to cocoa production) using traditional and modern fermentation systems that the manufacturing cost depended on agriculture costs, post-harvest costs, and fixed charges, which are a function of the type of business organization [26]. In Ghana, they analyzed the production cost of cocoa and showed that the average production cost, including all activities prior to fermentation, drying, and final transportation to the transformer, was USD$0.18 (COP$684) [27].This value was a lower cost than that reported by the National Federation of Cocoa Growers, Colombia (Fedecacao).

4. Conclusions

- The drying of cocoa beans in greenhouse-type structures is a procedure with low efficiency. The characterization of the drying process of cocoa beans reached 12.94% thermal efficiency.
- The costs associated with the drying process are related to the price per kg of fermented grain, labor employed, and greenhouse

Table 3 Summary results

Variable	How was it measured?	Specifications
Grain Temperature $[^\circ C]$	9 points, inside the greenhouse.	T. Laser: Accuracy $\pm 1.5\%$, resolution 0.1$[^\circ C]$
Ambient Temperature $[^\circ C]$	Portable thermohygrometer outside.	Goove: accuracy $\pm 0.5^\circ C / \pm 3\%RH$. Resolution 0.1$[^\circ C]$ / 1RH
Relative humidity [%RH]	Portable thermohygrometer inside.	Goove: accuracy $\pm 0.5^\circ C / \pm 3\%RH$. Resolution 0.1$[^\circ C]$ / 1RH
Radiation $[W/m^2]$	Pyranometer outside.	Kipp& Zonen: precisión 10%
Mass [g]	Measure per hour, 3-grain batch 1kg c/u.	Digital Scale: accuracy ± 0.1 g, resolution 0.2g

investment. The specific drying cost of $\sim 2,27USD\$/\mathrm{kg}_{\text{dry,cocoa}}$ $(10209COP\$/\mathrm{kg}_{\text{dry,cocoa}})$ is derived from the sum of those specific costs.

- Despite being a thermally inefficient process, the greenhouse-type structure is viable since it meets the objective of reducing grain moisture to the desired value with low operating and investment costs due to no associated costs because the fuel needed for drying is solar energy. Culturally, Labor costs are not considered because cacao is not a primary production in medium and small cacao farms: they prefer to produce plantain or mango, anyway "grain to bar farmers", those who cultivate cacao and produce chocolate bars in the same site, are exploring new opportunities with an organic product to improve labor payments [5].
- The drying rate of the cocoa bean was higher on the first day since there was a more significant amount of moisture inside the beans. This caused the moisture closest to the surface to come out first, then the moisture inside the grains. Moisture displacement within the grains was governed by diffusion and capillarity, and not for radiation, since they were not saturated with water, while for the second day of decreasing rate, it could be attributed to flow due to shrinkage, pressure gradients and gravity.
- There was saturated liquid in the environment greenhouse due to the drops of water perceived when entering it. In terms of drying the cocoa bean, this effect delayed reaching the cocoa bean's humidity of 7%, since these water drops condensed on the cocoa, as observed daily at the beginning of the mass vs. time curve.

5. Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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8. Author contributions

Juan Felipe Vásquez-Uribe: Experimental Setup, Writing - Original Draft, Writing, Investigation, Formal analysis. Juan Sebastián Vásquez-Alzate: Experimental Setup, Writing - Original Draft, Writing, Investigation, Formal analysis. José Alejandro Urrego-Pabón: Experimental Setup, Writing - Original Draft, Writing, Investigation, Formal analysis. Juan F. Pérez Bayer: Funding acquisition, Project administration, Writing, Conceptualization, Methodology. Edwin Chica: Project administration, Writing , Conceptualization, Methodology

9. Data availability statement

In Table 3, there is a summary of which instruments and equipment were used to collect all the information we present in this paper..

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