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Performance of solar dryer with thermal energy storage in brazilian cerrado region

Rendimento de secador solar com armazenamento de energia térmica em região do cerrado brasileiro

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ABSTRACT

Solar drying is an important technique for preserving food and agricultural products. This is a form of energy that has developed, as it is sustainable and low cost, however its intermittent nature is a limiting factor. Thus, the objective was to evaluate a solar dryer with integrated to a paraffin-based thermal energy storage system, as a phase change material (PCM), in the Brazilian cerrado region. Two dryers were built: one with PCM (Dryer 1) and the other without (Dryer 2). To carry out the experiment, the banana apple was dried in three experiments, corresponding to the days of exposure of the equipment to the sun. The dryers were evaluated for thermal efficiency and mass efficiency. The highest temperature measured was 71.7 °C for Dryers 1 to Experiments 1 and 2. The highest thermal yield observed was for dryer 2, with 45.82%. Dryer 1 showed higher mass efficiencies in the three drying days. Both dryers are suitable to produce dried bananas.

Keywords: Drying, Paraffin, Efficiency, Heat.

RESUMO

A secagem solar é uma importante técnica para conservação de alimentos e produtos agrícolas. Essa é uma forma de energia tem se desenvolvido, por ser sustentável e de baixo custo, contudo sua natureza intermitente é um fator limitante. Assim objetivou-se avaliar um secador solar com integrado a um sistema de armazenamento de energia térmica, à base de parafina, como material de mudança de fase (MMF), na região do cerrado brasileiro. Foram construídos dois secadores: um com MMF (Secador 1) e outro sem (Secador 2). Para realização do experimento procedeu-se a secagem de banana maçã, em três experimentos, correspondentes aos dias de exposição dos equipamentos ao sol. Os secadores foram avaliados quanto ao rendimento térmico e eficiência mássica. A maior temperatura mensurada foi de 71,7 °C para o Secadores 1 aos Experimentos 1 e 2. O maior rendimento térmico observado foi para o secador 2, com 45,82%. O secador 1 apresentou maiores eficiências mássicas nos três dias de secagem. Ambos secadores são adequados para produção de bananas secas.

Palavras-chave: Secagem, Parafina, Eficiência, Calor.

1 INTRODUCTION

Drying is one of the oldest and best-known techniques for preserving food and agricultural products. This technique consists of a product dehydration process, to promote greater stability and shelf life, which facilitates transport and commercialization, in addition to reducing chemical or microbiological deterioration mechanisms (OLIVEIRA et al, 2018). Although it is essential, drying can be costly and of high energy consumption, in which fossil fuels are mainly used (LADIMI et al, 2019).

Thus, sustainable drying alternatives are needed. Among the existing ones, solar drying is a method widely discussed in the literature, mainly because it is renewable and of low cost. The central-west region of Brazil, largely covered by the cerrado biome, can use solar energy, once an average solar irradiation incidence of 5.20 kWh / m^2.day (PEREIRA et al, 2017).

However, the use of solar energy is limited due to its intermittent nature, that is, its total or partial unavailability due to the night or cloudy days. In this sense, the number of studies on the storage of solar thermal energy has increased in recent years. In a special way, latent heat storage has advanced, since it requires a smaller volume for a greater amount of captured energy, especially through the so-called phase change materials (PCM) (BAL et al, 2010).

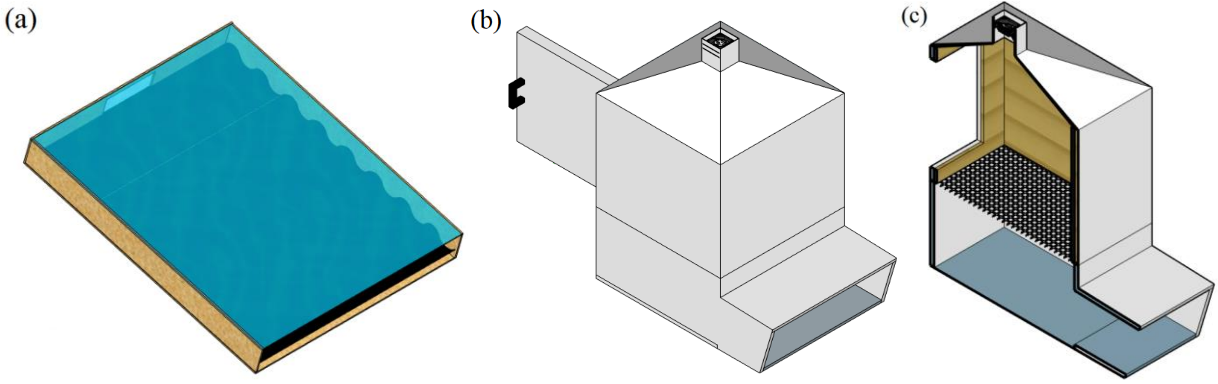
In the literature there are many studies that study this form of drying agricultural products, in which paraffin is the most applied PCM (BAHARI et al, 2020; LAKSHMI et al, 2018; AGARWAL and SARVIYA, 2017; RABHA and MUTHUKUMAR, 2017). Although there are many recent studies on the use of paraffin as MMF in drying, rare are those that apply in Brazilian regions. Therefore, the objective of this study was to evaluate the performance of a low-cost solar dryer, integrated with a thermal energy storage, with paraffin based PCM, in the Brazilian cerrado region.

2 MATHERIAL AND METHODS

2.1 DRYER CONSTRUCTION

Two dryers were built: one with thermal energy storage system (TESS), with paraffin based MMF, and the other without storage, here called dryer 1 and dryer 2, respectively. For the construction of solar dryers, the following basic structures were used: solar collector and drying chamber. The solar collector was a flat plate (1.15 m long, 1.00 m wide and 0.15 m deep), with a glass cover 4 mm thick. A fiber cement tile, painted black, acted as a thermal capacitor (Figure 1a). The drying chamber has internal dimensions with a square base area of 0.30 m x 0.30 m and 0.48 m in height. A perforated plate support was allocated inside. The chamber walls are made of insulating material (glass wool) between two sheets of wood. The air inlet consists of a rectangular nozzle of 0.30 m x 0.13 m. The top of the dryers was in the shape of a pyramid trunk of 0.07 m high, with a 0.05 m square exhaust fan on the sides. At the rear, doors for handling were used, with dimensions of 0.20 m x 0.20 m (Figure 1b). The constructive difference between dryer 1 and 2 was due to the coating of the internal walls with polyvinyl chloride (PVC) lining in dryer 1, filled with paraffin, characterizing the TESS (Figure 1c). All structures were painted black to optimize heat conservation and absorption.

Figure 1. Views of the structures used in the construction of solar dryers: solar collector (a), drying chamber (b) and drying chamber of dryer 1, with TESS (c) (structures shown in white to facilitate the visualization)



2.2 DRYING PROCEDURE

Drying was carried out in an experimental field, at the Federal University of Mato Grosso, Rondonópolis Campus, at latitude 16˚ 27 '49 "S, longitude 55˚ 34' 47" W. For study and evaluation of the dryers, drying was carried out banana (*Musa spp.*), cultivate apple, in three days: January 15th, 16th and 31st, 2020, thus characterizing three distinct experiments (Experiment 1, 2 and 3). Each experiment corresponds to the exposure of dryers to the sun, due to the different climatic conditions observed between them. For this purpose, four repetitions, with approximately 10 g of the product, cut into slices, were placed in petri dishes, and arranged inside the drying chamber of each dryer. The solar collector was attached to the drying chamber with an inclination of 16º, equivalent to the local latitude, so that the sun's rays strike perpendicularly, providing greater energy use. For the same purpose, the dryers were arranged with the glass cover facing north-south.

Figure 2. Dryer 1 (top) and dryer 2 (bottom) operating in an experimental field at the Federal University of Mato Grosso.

2.3 PERFORMANCE EVALUATION OF DRYERS

To study the performance of dryers, First Law of Thermodynamics (Equation 1) was applied, which relates heat, work, kinetic energy and potential associated with a control volume, with the drying air as fluid.

$$\frac{\partial E}{\partial t}=\dot{Q}-\dot{W}+\sum_{e}\dot{m}_e\left(h_e+\frac{v_e{}^2}{2}+gz_e\right)-\sum_{s}\dot{m}_s\left(h_s+\frac{v_s{}^2}{2}+gz_s\right) \tag{1}$$

On what:

$\frac{\partial E}{\partial t}$: temporal rate of energy variation in the control volume, W;

$\dot{Q}$: heat transfer across the control volume boundary, W;

$\dot{W}$: transfer of work across the control volume boundary, W;

$\dot{m}$: mass flow, kg s^{-1};

h: specific air enthalpy, kJ kg^{-1};

v: air speed, m s^{-1};

g: gravity acceleration, m s^{-2};

z: absolute value of vertical position, height, m;

$_e$: control volume input;

$_s$: control volume output.

Thus, two volumes of controls for the evaluation of the dryers were distinguished, in view of their constructive specifications: the first, being the solar collector, which is equivalent to the thermal performance of the dryers, and the second, the drying chamber, corresponding to mass efficiency.

A) Thermal Performance:

To calculate the thermal efficiency of the dryer, the construction characteristics of the control volume must be considered, in this case, the solar collector. Thus, the kinetic and potential energies of the same are null, since there is no movement, and it is possible to verify that there is no work. Therefore, from this premise, Equation 1 was used, and it is possible to deduce Equation 2:

$$\dot{Q}_{e\text{-}s}+\dot{m}_e h_e=\dot{m}_s h_s \tag{2}$$

where $\dot{Q}_{e\text{-}s}$ represents the transfer of energy that occurs across the boundary of the control volume to the working fluid, that is, the drying air. Accept that the incoming mass flow is equal to the outflow, you can rewrite Equation 2 as:

$$\dot{Q}_{e\text{-}s} = \dot{m}\,(h_s\text{-}h_e) \tag{3}$$

Mass flow was calculated by applying air velocity data inside the solar collector (measured by a hot wire anemometer, F-900) to Equation 4:

$$\dot{m} = \rho V A \tag{4}$$

On what:

ρ: specific gravity of the working fluid, kg m^{-3};
V: speed of the working fluid within the control volume, m s^{-1};
A: Fluid inlet area in the control volume, m^2.

Therefore, the thermal efficiency of the dryer is equal to the ratio between the energy transferred into the control volume ($\dot{Q}_{e\text{-}s}$) and the Solar Irradiation incident on the area of the transparent cover of the collector ($\dot{Q}_{solar}$) , which, in turn, is the product between the coverage area (A_c) and the hourly solar radiation for the day ($\dot{Q}_{solar\text{-}hourly}$) (Equation 5).

$$\eta_{collector} = \frac{\dot{Q}_{e\text{-}s}}{\dot{Q}_{solar}} = \frac{\dot{m}\,(h_s\text{-}h_e)}{A_c \cdot \dot{Q}_{solar\text{-}hourly}} \tag{5}$$

B) Mass Efficiency:

The control volume applied to the drying chamber has different mass flow rates, that is, the mass of the incoming air is less than the mass of the outgoing air, which contains the increase in the mass of water resulting from the dehydration of the product.

From the constructive specifications of the chamber, it can be inferred that the kinetic energy and powers at the entrance and the exit are the same, and the work is zero. Thus, it can be said that the drying chamber acts as a sink, since in these thermodynamic systems the T inlet is equivalent to the outlet, observing such behavior for the dryers. Thus, applying these findings to Equation 1, we have that the mass efficiency is equal to:

$$\eta_{chamber} = \frac{m_i - m_f}{m_w} \cdot 100 \qquad (6)$$

On what:

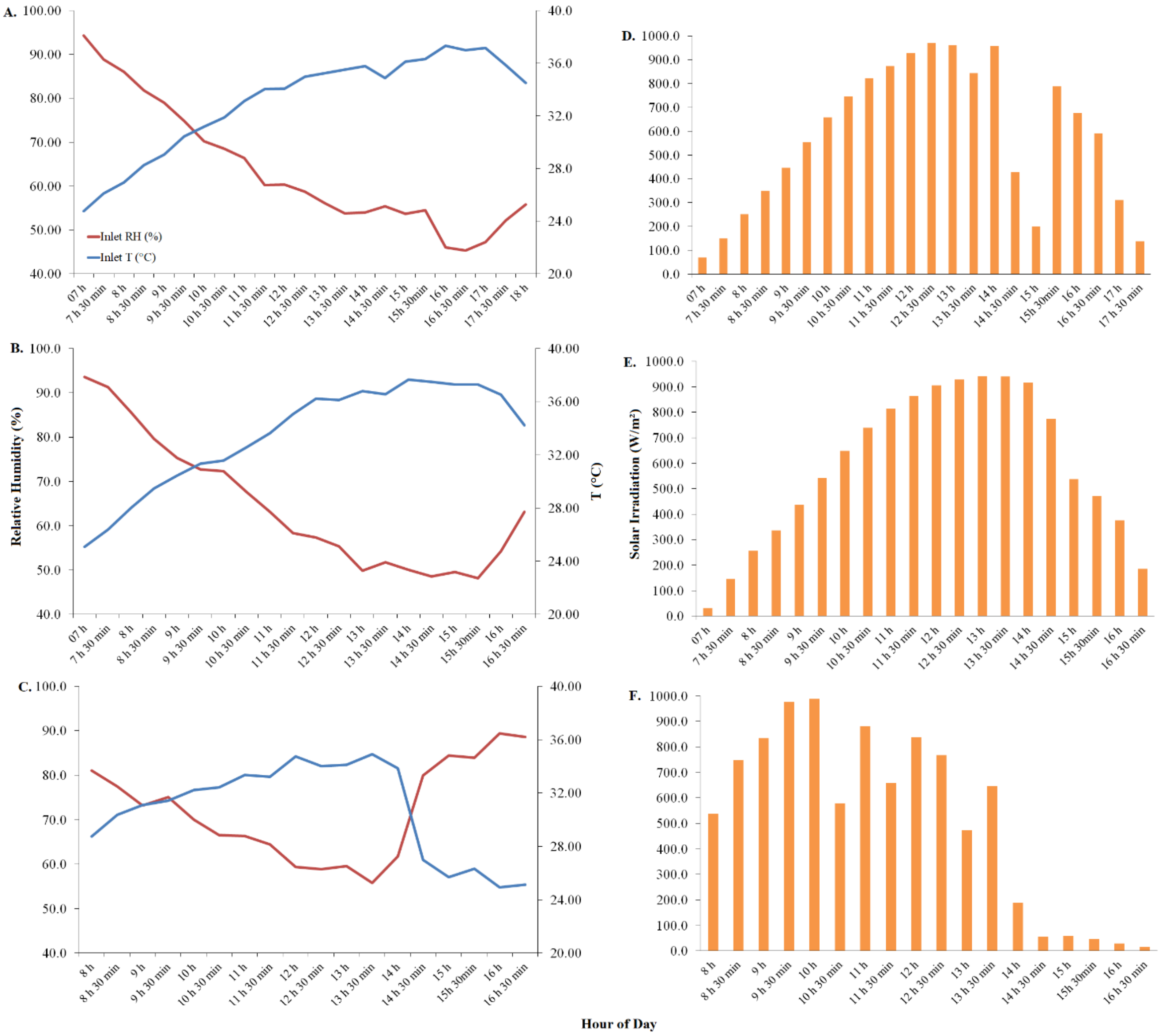
$\eta_{chamber}$: mass efficiency of the drying process, %;
m_i: initial product mass, g;
m_f: final product mass, g;
m_w: total water mass of the product to be dried, g;

The enthalpy data (input and output) and specific mass were estimated from the temperature (T) and relative humidity (RH) data of the ambient air. These values were recorded in the Computer Aided Thermodynamic Tables 3 software, through which the required information was estimated, using electronic psychrometric graphs. The incoming T and RH magnitudes, as well as the hourly solar irradiation magnitudes, were provided by the meteorological station installed inside the UFMT Campus. The T and RH of the collector-chamber junction, equivalent to the collector outlet and chamber entrance, were obtained using the HT-70 sensor (Instrutherm). The initial and final masses of the product were determined by weighing, immediately before and after dehydration in dryers 1 and 2, applying humidity test according to Instituto Adolfo Lutz (2008). The difference between the initial and dry mass of the banana samples in the moisture test corresponded to the total water mass.

3 RESULTS AND DISCUSSION

The climatic data (temperature, relative humidity and hourly solar radiation) for each drying experiment are shown in Figure 3.

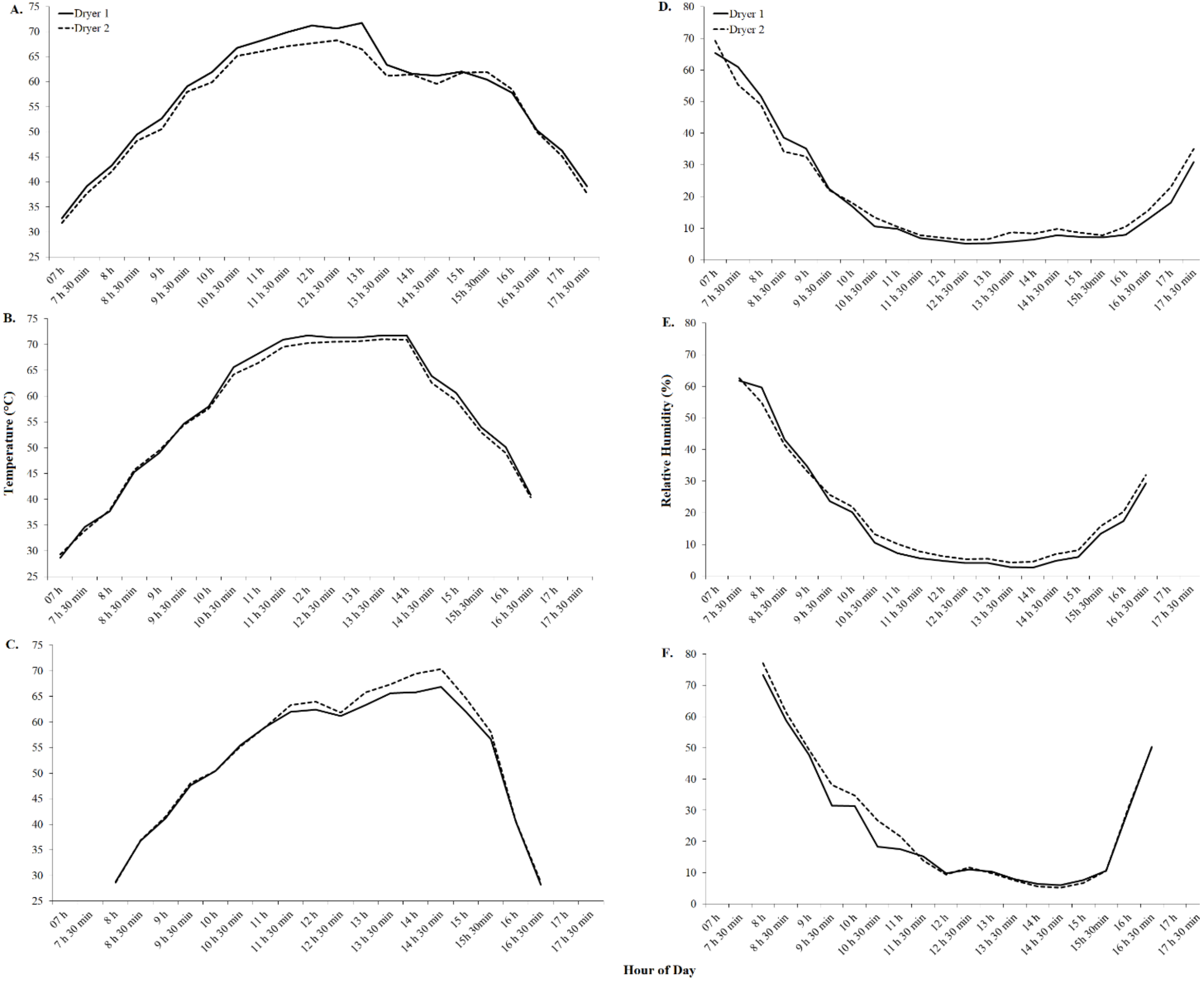
Figure 3. Variation of climatic data of relative humidity (RH), temperature (T) and hourly solar irradiation (Q) for Experiment 1 (A and D), Experiment 2 (B and E) and Experiment 3 (C and F)



As shown in Figure 3, it is noted that the drying of the banana-apple was not carried out for equal periods of drying. This fact stems from the different climatic conditions of each day, with the occurrence of rains that prevented the exposure of dryers. Thus, the drying periods were 11 hours, 9 hours and 30 minutes and 8 hours and 30 minutes, for Experiments 1, 2 and 3, respectively. Considering the relative humidity and temperature data in Experiments 1 (Figure 3a) and 2 (Figure b) it is noted that they were relatively similar. The peak temperature for both was just above 37 °C, while the RH was maximum at the beginning of drying and had its minimum value between 2 pm and 4 pm. The hourly radiation for these days (Figures 3d and 3e) behaved in a similar way, with a peak above 900 W m^{-2}. A sharp drop in irradiation rates is seen in Experiment 1, which may indicate possible shading. For Experiment 3, it was characterized as a cloudy day with rainfall in the late afternoon, which is observed in the sudden rise in relative humidity (Figure 3c), at the time of day when it should have its lowest magnitude, and a fall accentuated in temperature (Figure 3c). The solar radiation did not behave in a homogeneous way, oscillating throughout the day due to the partially overcast sky, where from 2 pm onwards its values dropped due to rain. The condition found for Experiment 3 was important to mitigate the effect or not of TESS on Dryer 1.

The properties of relative humidity and temperature of the drying air, after passing through the collectors, are shown in figure 4.

Figure 4. Variation of the relative humidity (RH) and temperature (T) data of the drying fluid (drying air) after passing through the solar collector, in Experiments 1 (A and D), Experiment 2 (B and E) and Experiment 3 (C and F).



The temperature peaks for dryers 1 and 2 were 71.7 and 68.3 ° C, 71.7 and 71.0 ° C, 66.90 and 70.30 ° C, respectively in Experiments 1, 2 and 3. It is observed that thermal storage provides conditions higher temperatures and days with more regular solar radiation conditions, which was recorded on January 15th and 16th.

According to the data, the rate of increase in temperature in Dryer 1 was, on average, 6.50, 8.60 and 5.02 ºC per hour, until the temperature peak, while the ambient T increased at a rate of 1.75, 2.45 and 0.91 ºC per hour, for Experiments 1, 2 and 3, respectively. Therefore, on January 15th, 16th and 31st, with each degree of rise in room temperature, Dryer 1 raised 3.71, 3.51 and 5.52 °C. In the case of Dryer 2, without TESS, the air warmed up from 6.12, 6.18 and 5.57 ° C for each hour of exposure to the sun, until the peak of T, in a respective way for each experiment. In this dryer, 3.50, 2.52 and 6.12 °C were added to each degree of rise in ambient temperature.

According to Baniasadi et al. (2017), in his experiment the highest temperature recorded was 50 ° C, at 2:30 pm, located at the outlet of the solar collector. The temperature inside the drying system increases at a rate of 5 ° C per hour before noon and decreases twice as fast in the afternoon.

Although there was no constructive difference between the solar collectors of each dryer, it was noted that the behavior of T was different between them. This fact can be justified by the fact that the solar dryer not only absorbs heat by the collector, but also by the side walls of the drying chamber, which in turn, differ between the presence and absence of TESS. Thus, TESS influenced the heating rate, even though the solar collector had similar construction characteristics.

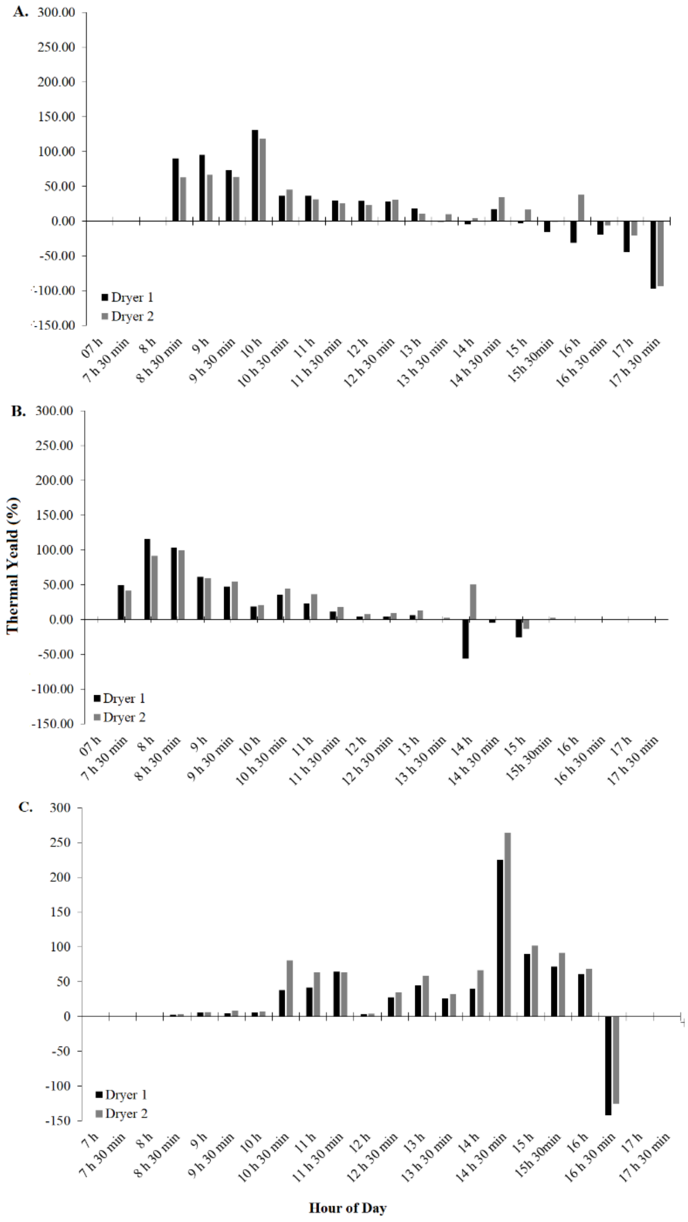
The air humidity in Dryer 1, after undergoing heating, varied between 5.1 and 65.4%, 2.6 and 61.7%, 6.1 and 73.3%, in a manner corresponding to the three days of conducting the experiments. Dryer 2 showed humidity variations between 6.3 and 69.2%, 4.2 and 62.5%, 5.3 and 77.1%, respectively on January 15th, 16th and 31st. The highest RH were measured immediately after drying started. The lowest humidity corresponded to the peak temperature.

n the study conducted by Azaizia et al (2020), for drying red pepper, two greenhouses with identical solar heaters were used, one with paraffin (PCM) and the other without. The greenhouse that had the PCM reached temperatures up to 7.5 ° C higher and humidity 18.6% lower than the one without material.

Thus, it is noted that Experiment 2 was the one that best evidenced the effect of TESS. The same was a day with more homogeneous climatic conditions than the others, with regular behavior for T, UR and $\dot{Q}_{solar\text{-}hourly}$. On that day, Dryer 1 showed the peak of T at noon, with 71.7 °C, remaining for two hours, while Dryer 2, 71 °C at 13 h 30 minutes, remaining for one hour. Therefore, storage contributed to a higher temperature peak, as well as a longer duration. However, in Experiment 3, the day with the greatest oscillations in the hourly solar radiation, Dryer 2 had a peak of 70.3 °C, and Dryer 1, 66.9 °C. This difference may have been justified by the fact that the energy initially supplied by the drying fluid is used to heat the TESS, which after accumulating heat releases it to the system. As there was a greater variation, the heat supplied was used for the initial heating of the PCM. The main factor that influences the outlet temperature of the collector is solar radiation, since the mass flow is constant (LAKSHMI et al, 2018).

From the data of T and UR, both input and output of solar collectors, the thermal yield of each dryer was determined, expressed in figure 5, which shows its variation over the drying period.

Figure 5. Variation in the thermal perfonmance of dryers 1 and 2 over the drying period in Experiments 1 (A), 2 (B) and 3 (C).



The average yield for Dryers 1 and 2 was 16.85% and 20.98%, on January 15th; 19.52% and 26.69%, on January 16th and 33.70% and 45.82%, on January 31st. In experiment 1, the peak thermal performance was at 10 am, for both dryers, with a value of 131% for TESS, and 118% for sem. The maximum efficiency in experiment 2, was reached at 8 am in dryer 1, with 115.80%, and at 8 am and 30 min in dryer 2, with 99.10%. In turn, in experiment 3, the peak was reached in the afternoon, due to climatic conditions, with 224.87% for the dryer with the PCM and 263.82% for the dryer without the material, both at 14 h and 30 min.

It is observed that the dryers showed the behavior of accumulating energy in the morning, so the yield was increasing until peak hours. Accordingly, the sun's rays no longer strike perpendicularly to the collectors, due to the movement of the sun, the dryer tends to give energy to the environment, characterizing the negative points. In experiment 2, the sharp drop in the thermal performance of dryer 1 noticed at 2 pm, possibly due to some shading.

The higher average yields of dryer 2 compared to 1, even with the same structures, are due to TESS, which provided a drier fluid. The average RH of output in dryer 1, considering experiments 1, 2 and 3 were 30.43, 19.59 and 24.71%, respectively, while in dryer 2, 31.85, 20.79 and 26.18%. As the humid air has a higher specific heat in relation to the dry air, due to the properties of the water, there was a greater energy associated with that equipment that presented a humid air. A similar behavior was found in the study by Bhardwaj et al (2019) in the drying of *Valeriana jatamans,* in the Himalayan region, with higher yields for the collector without storage compared to the presence of paraffin.

The performance of the solar collector in Experiment 3 showed a higher average efficiency compared to Experiments 1 and 2, even with cloudy conditions. Such higher values, in comparison to the other experiments, can be justified by the low $\dot{Q}_{solar\text{-}hourly}$ at peak time, while the thermal capacitor continued to yield heat to the air, promoting heating of the fluid with low solar radiation. On the other hand, it presented the most negative values for thermal yield at 16 h and 30 min, due to practically no solar radiation at this time, due to the formation of rainy weather, noticed by the sudden increase in UR and T at 15 h and 30 min.

SunilRaj and Eswaramoorthy (2020) obtained a maximum thermal efficiency of 65% in a solar dryer, using Paraffin as PCM. Khadraoui et al (2018) in turn, integrated the PCM to the solar collector, which showed an average efficiency of 33.9%. Rabha and Muthukumar (2017) reached a peak of 40.2% in thermal yield for a flat plate solar heater, in drying ginger and ghost chilli pepper, in the northeast region of India. Morais et al (2019) used an indirect solar dryer, without TESS in the drying of papaya seeds, in which the solar collector obtained an average yield of 45% and a maximum temperature of 53 °C, in the Northeast region of Brazil.

The average data of initial and final banana mass after dehydration in Dryers 1 and 2, for the three drying days are shown in Table 1, as well as the dry mass values and initial and final moisture estimated by the water content test. and the mass efficiency calculated from these values.

Table 1. Average data of initial, final and dry masses, initial and final humidity of banana samples and mass efficiency of dryers 1 and 2.

Dryer	m_i	m_f	m_d	M_i	M_f	$\eta_{chamber}$
			Experiment 1			
1	8.89	2.78	2.21	75.16	6.39	91.50
2	8.32	2.85	2.09	74.90	8.77	88.28

			Experiment 2			
1	7.27	2.24	1.79	75.42	6.11	91.90
2	8.27	2.93	2.04	75.32	10.61	85.90
			Experiment 3			
1	8.22	3.46	2.05	75.09	17.21	77.07
2	7.91	3.50	1.97	75.05	19.03	74.65

m_i: initial mass of the product, g; **m_f:** final mass after drying in the dryer, g; **m_d:** dry mass at the end of the moisture test, g; **M_i:** initial humidity, before drying in the dryer, on a wet basis,%; **M_f:** final humidity, after drying in the dryer, on a wet basis,%; **$\eta_{câmara}$:** mass efficiency,%.

It is observed that in all experiments, dryer 1 promoted a drier final product compared to dryer 2. This fact can be justified by the fact that the drying air was less humid, so there was a greater humidity gradient between the air drying and the product, which intensifies the movement of water from the fruit surface to the air, and consequently drying.

Morais et al. (2019) when drying papaya seeds reduced the water content from 83.08 to 7.22%. Atalay (2019) reduce the water content of orange slices from 93.5% to 10.28%, with an integrated solar dryer with thermal storage system for sensitive heat, by means of a compacted bed. Lakshmi et al (2018) obtained samples of *Curcuma caesia* with 8.5% moisture, after 18.5 hours of drying in a solar dryer with paraffin-based heat storage, in which the initial water content was 73.4%.

According to Collegiate Board Resolution (RDC) No. 272, of September 22, 2005, of the National Health Surveillance Agency (ANVISA), for a fruit to be considered dry, it must have a maximum of 25% b.u. moisture content. Therefore, both dryers can produce dried bananas, according to the RDC, if there is control over the drying period. The low final water content of the product is related to the drying time to which it was exposed and its cut shape. To obtain a dry fruit, it is essential to have control of the drying time to achieve desirable percentages.

Although both dryers are suitable to produce dryed bananas, dryer 1 showed better mass efficiency compared to 2. Therefore, PCM contributed to obtain drier products, in the same drying period, when compared to drying without TESS. It is noted that experiment 2 demonstrated more the difference between the values of $\eta_{chamber}$, while experiment 3, characterized as a cloudy day, the smallest differences, although Dryer 1 still stood out on 2. Thus, it is noted that the storage from paraffin was efficient to promote greater drying efficiency.

Murali et al (2020) built a hybrid dryer, with water-based thermal energy storage, which obtained a maximum efficiency in drying shrimp of 37.09%. Bhardwaj et al (2019) reached a maximum η of 27.84%, with storage of thermal energy, in the drying of medicinal plants.

4 CONCLUSIONS

The PCM solar dryer promoted higher temperatures and lower humidity of the drying air in the first two days of the experiment compared to the one without thermal energy storage.

A higher thermal yield occurred for the dryer with TESS, in the first two days of drying.

The dryer integrated with PCM promoted drier products in the three experiments.

Both dryers are suitable to produce dried bananas, however the TESS dryer showed higher mass drying efficiency in the three drying procedures.

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