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Performance Improvement of a Hybrid Biomass / Indirect Solar Dryer (HBISD) for Drying Guava (Psidium Guajava)

G.B. Tchaya[1], E. Tchoffo Houdji[1], Moktar Garga[1], B. Kaldambe Zoua[1], J.L. Nsouandele[1]

[1] Department of Renewable Energy, National Advanced School of Engineering- University of Maroua

Corresponding author: tchayaguy@gmail.com

Abstract

This work aims to improve an indirect solar dryer by adding a biomass energy source with a storage system. A Hybrid Biomass - Indirect Solar Dryer (HBISD) was designed and made from local materials. Solar energy and improved charcoal (30 MJ/kg) stove (Jambar type) with a thermal storage system using pozzolan supply the drying chamber. Measurements of irradiance and in and out dryer chamber temperatures were carried out in three drying modes with and without energy storage: indirect solar, biomass, and hybrid. The solar collector designed has an area of 0.2 m², and the drying chamber volume is 0.402 m^3. The volume of the fireplace is 0.012 m^3. The experimental results show that the highest drying room temperature is 52 °C at 940 W / m² for the solar collector test, while for the different masses of charcoal (200, 400, 600, and 800 g) in the fireplace, it is 40.6 °C, 55.33 °C, 63.2 °C, and 62.31 °C respectively. Using a mixture of charcoal and pozzolan in the mass proportion of 20%, 30%, and 50% of pozzolan, it is shown that the temperature in the drying room reaches 71.37 °C, 64.28 °C, and 60.02 °C, respectively. The autonomy due to the storage system is 02 hours 05 minutes, 01 hours 20 minutes, and 01 hours 15 minutes respectively for temperatures above 50 °C. The quantity of charcoal used in the storage case is less than that in its absence for the same duration and drying room temperature. In hybrid mode, the drying of guava has a shorter drying duration (7 hours) than that obtained in indirect solar mode (26 hours).

Keywords: solar dryer, hybrid system, biomass dryer, energy storage, pozzolan, charcoal.

Nomenclature

η_c : Collector efficiency, (%)

$\dot{M}_a$: Mass flow rate of air (kgh^{-1})

T_{co} : Collector outlet temperature (°C)

T_{am} : Ambient temperature (°C)

T_{chamb} : Drying chamber temperature (°C)

C_p : Specific heat of air (Jkg^{-1} °C^{-1})

A_c : Collector area (m²)

I_c : Average solar radiation incident on the collector ($MJm^{-2}h^{-1}$)

t_d : Time (s)

Q: Heat transmitted to the drying air $\left(^{Kcal}/_{h}\right)$

T_s: Hot fluid outlet temperature of the pipe

T_e: Inlet temperature of the hot fluid of the pipe

PCI : lower heating value (MJ / Kg)

m : Mass (kg)

V: Volume of the drying chamber (m3)

L: Length of the chamber (m)

W: Width of the chamber (m)

H: Height (m)

Introduction

In many countries worldwide, the sun's rays are widely used as a direct source of energy to dry food products. As a means of preserving food, solar drying is considered as one of the most widely used systems [1]. The availability of some food over the year is a real problem because, after the harvest season, products are not available on the market due to the lack of post-harvest conservation means. When these are available, their quality is poor due to deplorable conservation practices [2]. Therefore, there is a problem linked to food security that has negative repercussions on the local economy. Drying appears to be the best way to stabilize these products for later use, as it reduces the volume of water in the products by more than 90% [3]. The development of increasingly efficient drying techniques and technologies is of interest in dealing with the conservation of post-harvest products [4]. Drying can be done in different ways depending on the cost, drying mode, the flux air mode in the drying chamber, and energy sources. Thus we can distinguish according: to the cost, industrial and traditional dryers [5]; to the nature of energy sources: solar, biomass, and fossil fuel dryers [6]; to the mode of drying: open sun, indirect solar dryer and mixed-mode [7–10]; to the flux air mode in the drying chamber: natural air convection or forced air convection, vertical, parallel or turbulent airflow mode [11–13].

Concerning drying with solar energy, a significant limitation is the nature of the solar radiation, which depends on time. The availability of solar energy only during sunny hours makes it difficult to use this energy source when the sun is absent without additional auxiliary heat [14]. The mentioned problems demonstrate the importance of designing news drying units for achieving the best drying qualities. Some of these problems can be mitigated by using an energy storage system with phase change materials (PCM) [15–17], with sensible heat storage material (SHSM) that can be classified in liquids (water, Caloriea HT43, Glycerin, Liquid Paraffin, Molten salt, Engine oil), in solids (Rock, Sand, Bricks, Granite, Pebble stones) and organic liquids (Ethanol, Proponal, Butanol, Isobutanol, Isopentanol, Octane) [6,7,18]. Ndukwu et al., 2020 [19] show, for example, that a forced convection mixed-mode solar (FCMS) dryer with latent heat storage reduces the drying time by approximately 50% compared to the traditional method of natural open sun drying.

The heat stores in those storage systems can be produced by solar irradiation, conventional electricity, photovoltaic energy, biomass, and fossil fuels. Thus many hybrid dryers use biomass [20–22], conventional energy [21] or photovoltaic systems [23–25] to power resistors as heat back up energy system to continue drying products during cloud periods and night and though to improve the performances of drying systems to reduce the moisture content of the crops or biomass waste, have been built and characterized. Others also use fossil energy sources in hybrid solar dryers as heat backup energy systems, but these energy sources pollute the environment. Their cost is high, and their availability in the future is compromised [26]. On the one hand, the efficiency of the dryers equipped with biomass heaters depends on the nature of the biomass to be used [27]. On the other hand, these dryers can save time compared to the open sun drying method for example. Ndukwu et al., 2020 [28] show that a solar dryer equipped with a biomass heater can save between 27.78% and 58.33% of drying time compared to the open sun drying method at an ambient temperature ranging between 30 and 40 °C and humidity ranging from 55% to 70%. So it is crucial to choose the appropriate dryer for agricultural products depending on the availability of diverse energy sources to be involved in the drying process.

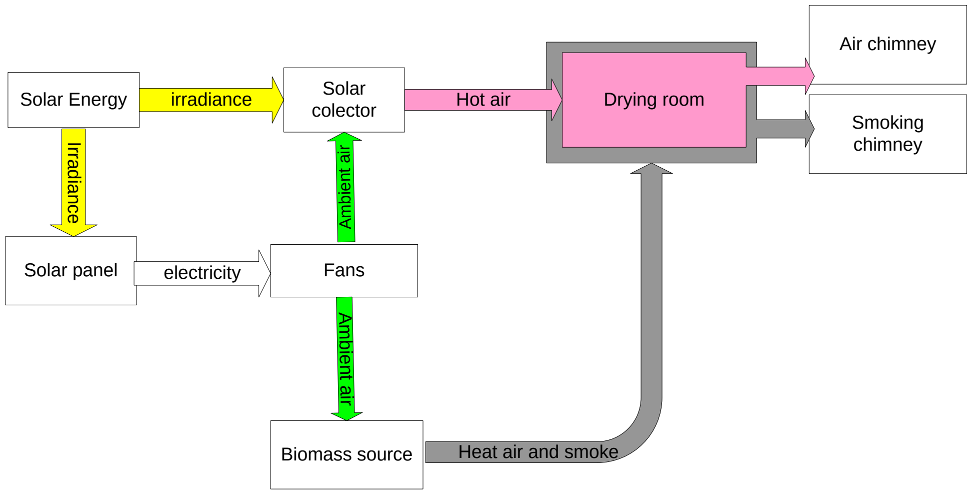
This work aims to improve the performance of an indirect solar dryer by adding a biomass energy source using charcoal as raw material and pozzolan to store heat to be used during cloudy day and night.

I. Materials and Methods

I.1. Operating principle of the Hybrid Biomass - Indirect Solar Dryer (HBISD)

The Hybrid Biomass - Indirect Solar Dryer (HBISD) comprises a solar collector is operating by forced convection, a drying chamber with several racks and two chimneys, and a biomass energy source. The figure 1 below shows the operating principle of the system.

Solar energy with the same power is reaching the solar collector and solar panel. The electricity provided by a solar panel supplies fans used for forced convection of the air in the solar collector and stir up the air in the biomass source. The heat from the two energy sources feeds the drying chamber simultaneously.



Figuere 1. Operating principle of the Hybrid Biomass - Indirect Solar Dryer (HBISD).

I.1.1. Solar collector

The components used to produce solar energy sources are described in table 1. The solar collector is the part of the indirect solar dryer that provides heat energy to the drying room.

The solar collector consists of:

- A glass roof having transmission coefficients (α) and emission (ε) equal to 83% and 90% respectively, with different wavelengths;
- A black-painted smooth aluminum absorber having absorption and thermal conductivity coefficients of 95% and 204 W/m **°C,** respectively;
- Wooden insulation is resistant to temperatures greater than 90 ° C and having a coefficient of thermal conductivity equal to 0,15 W / m. ***°C***

➢ Collector efficiency, $\eta_c(\%)$,

It is defined as the ratio of heat received by the drying air to the insolation on the absorber surface, and is calculated from:

$$\eta_c = \left(\frac{10^{-6}\dot{M}_a(T_{co}-T_{am})C_p}{A_c I_c}\right) X\ 100 \qquad (1)$$

Where $\dot{M}_a$ is the mass flow rate of air required for drying (kgh^{-1}), T_{co} is the collector outlet temperature (°**C**), T_{am} is the ambient temperature (°**C**) , C_p is the specific heat of the air (Jkg^{-1} **°C^{-1}),** A_c is the collector area (m²) and I_c is the average solar radiation incident on the collector ($MJm^{-2}h^{-1}$)

➢ Collector area A_c

It is calculated from:

$$A_c = 10^{-3} Q / t_d I_c \eta_c \qquad (2)$$

Studies on solar collectors with glass cover have permitted to estimate the efficiency η_c of the collector at 60%, the specific heat of air C_p= 1008 J kg^{-1} °C^{-1}

The airflow is set by the fans used, so we have $\dot{M}_a$=0,033kg/s. The ambient temperature of the fluid at the inlet is T_{amb} = 24.9 °C, and the outlet temperature is between 50 $\leq T_{co} \leq$60 °C.

Considering the experimental area where the most unfavorable month of the year has irradiation Ic = 4.850kWh / m^2 / day.

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Table 1. Characteristics and role of material used in solar source

Designation	Characteristics	Roles
Wood	Thermal conductivity: 0.12-0.15 W/m °C Density: 375-525 kg/m^3	Ensuring good thermal insulation.
Transparent glass	Thermal conductivity: 0.78W/m°C Density: 2700kg/m^3 ;Thickness : 4 mm Transmission rate: 0.83-0.91	Allows solar radiation to pass through and stops infrared radiation at the solar collector.
Smooth aluminum sheet	Thermal conductivity : 204 W/m °C Density: 896 kg/m^3 ; Thickness: 0.8mm Absorption coefficient: 0.65 Emission coefficient: 0.09	Absorbs solar radiation and converts it into heat.
Matte black paint	Absorption coefficient: 0.9-0.95 Emission coefficient:>0.85	Coated on the absorber to obtain the best highest absorption coefficient and lowest emission
Fan	DC 12 V 0.14 A	Provided force convection of the air in the solar collector.

I.1.2. Biomass source Principle

The heat produced by the biomass fireplace was connected to the drying chamber through a gas to a gas heat exchanger to ensure that the hot air reaching the samples is clean, smokeless, and ash-free as propose by [29]. Table 2 shows the characteristics and role of the materials used. The improved fireplace is Jambar type [30], where we have adapted fans to stir up charcoal in the combustion chamber. The charcoal has been used but can be replaced by biochar, and we have added black volcanic stone (pozzolan) in the fireplace in specific proportions to store thermal energy in order to improve the efficiency of the equipment

Heat quantity transmitted to the drying air is:

$$Q = mC_p(T_e - T_s) \quad \text{(Kcal/h)} \qquad (3)$$

Ts: hot fluid outlet temperature of the pipe

Te: inlet temperature of the hot fluid of the pipe

Calculation of the amount of heat produced by the fireplace

It depends on the quantity of fuel and its PCI (lower heating value)

The PCI of coal is 30 MJ / Kg

$Q = m \times PCI$ **(4)**

Table 2. Characteristics and role of material used in biomass source

Designation	Characteristics	Roles
Fan	DC 12 V 0.14 A	Stirs up the coal in the combustion chamber
Improved fireplace	Type « Jambar [31]	Used as a backup source for our indirect solar dryer
Charcoal	27< PCI <32 MJ/kg	Combustible
Black volcanic stone	Theoretical heat capacity between 1000 and 1200 J/kg/K; Thickness is 10 mm.	Store heat

I.1.3. Drying chamber

The separation chamber is made of aluminum sheets and wood as thermal insulation.

A space between the insulating wood and the sheet of aluminum in contact with the drying chamber allows the circulation of the smoke and its evacuation through the chimney. The sheet transmits heat to the drying chamber by conduction. Furthermore, the smoke is not arriving at the drying room.

The drying room has two chimneys; an air chimney to evacuate saturated air after drying and a smoke chimney where smoke passes through.

$V = L \times W \times H$ (5)

V: volume of the drying chamber

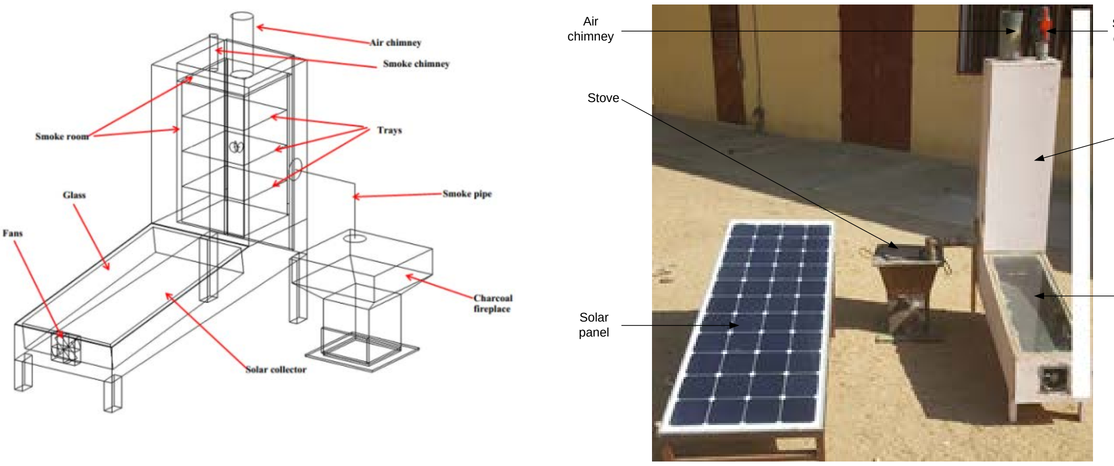
L: length of the chamber

W: width of the chamber

The drying chamber consists of 3 racks separated from each other by 20cm. Thus, we have the length L = 95cm, the width W = 35cm and the height H = 121cm

I.1.4. Technical drawing of the Hybrid Biomass - Indirect Solar Dryer (HBISD)

Figure 2a represents the sketch of the Hybrid Biomass - Indirect Solar Dryer (HBISD) to be implemented. The solar dryer is indirect, and the back-up source is an improved stove whose fuel is charcoal. The solar thermal collector has an area of 0.2 m^2, and the drying chamber has a volume of 0.402 m^3. The smoke chamber is separate from the drying chamber. This chamber is made of aluminum sheet and allows better heat exchange with the drying chamber. Figure 2b is the picture of implemented HBISD.



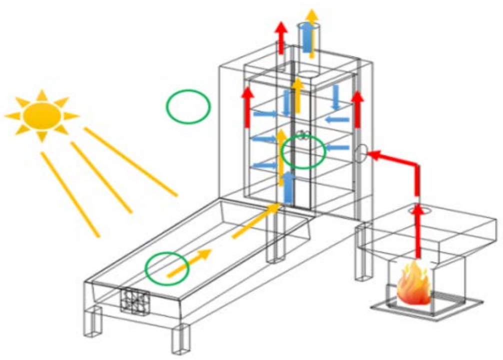
a) b)

Figuere 2. Hybrid Biomass - Indirect Solar Dryer (HBISD) a) Descriptive diagram b) photo.

I.3. Characterization of Hybrid Biomass - Indirect Solar Dryer (HBISD)

The characterization of the Hybrid Biomass - Indirect Solar Dryer (HBISD) is done through several experiments on the device with temperature sensors located as shown in figure 3. Firstly, vacuum tests to determine the system's functioning, and secondly, the drying of the guava to verify the improvement made by adding the biomass energy source to the indirect solar dryer.

Heat produce by solar collector
Heat getting in the drying
Heat produce by fireplace
Temperature sensor



Figuere 3. Experimental scheme of the drying system.

I.3.1. Hybrid vacuum dryer with solar collector

The experiment consists of putting the dryer on the sun and then orienting the flat collector to the south for better performance. After, the temperature probes are placed in the drying chamber, on the solar thermal collector, and outside the dryer (figure 3). The heat is produced by solar collectors only. A data acquisition system, Almemo 2390-8, automatically records the temperature values every 5 minutes. The irradiance is measured every 5 minutes using a solarimeter (multimetrix spm72).

I.3.2. Hybrid vacuum dryer with biomass supply

The improved fireplace was only used in this experiment (figure 3). The heat is produced by the fireplace only. First, the coals were characterized by measuring their weight. After loading the coal into the combustion chamber of the fireplace, they finally carry out the combustion.

Various tests were performed with different amounts of charcoal (200, 400, 600, and 800 g), and the volcanic stones are used as a storage system in different proportions (20, 30, and 50%) of the amount of material to be burned. When the fire is lit up, the stones have been added about 10 minutes after the combustion.

I.3.3. Hybrid vacuum dryer combined with improved fireplace and solar collector

The flat solar collector of the dryer and the fireplace were used (figure 3). Both places produce the heat. The dryer has been exposed to the sun, with the flat collector facing south for better performance. Characterized charcoal by measuring its weight is introduced into the combustion chamber of the fireplace for combustion.

After placing the temperature probes at the level of the drying chamber and outside the dryer to have the temperature at the level of the drying chamber and the ambient temperature, the data acquisition system, Almemo 2390-8, automatically records the values of these temperatures every 5 minutes. Sunshine is measured every 5 minutes using a solarimeter.

Four experiments were carried out with 200, 400, 600, and 800 g of charcoal that. Charcoal is added every 1h30mn on the combustion.

I. 4. Drying of the guava in hybrid mode

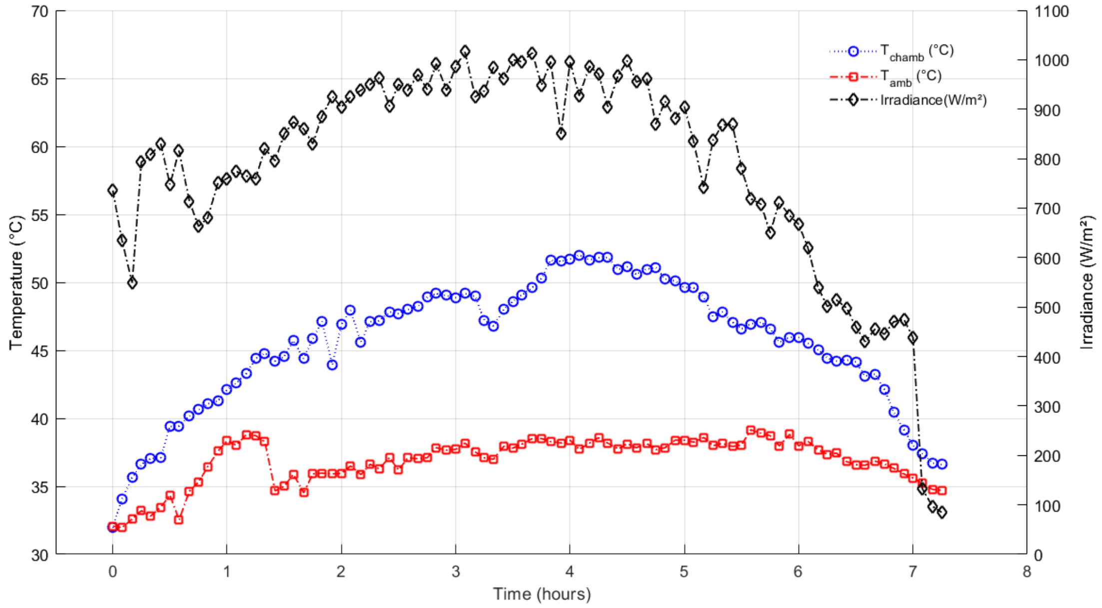
The drying of the guava (*psidium guajava*) includes a phase of preparation, drying, and conditioning. The Washing guavas involves removing impurities and dirt. The guavas are then thinness cut to allow better drying. After the product is spread in the dryer, and the drying process is continued until free water has been removed.

A mass of 60 g of product is spread per rack. To follow the product mass loss during drying, weight measurements are taken every 10 minutes then every 15, 30, and 60 minutes using a balance with digital display at 1/100. The drying kinetics of the guava are then plotted and analyzed.

II. Results and discussion

II.1. Performance of the dryer with solar collector

The performance of the dryer obtained during tests with a solar vacuum collector is shown in figure 4. It can be seen that, during this manipulation, the chamber temperature T_{chamb} reached 52 °C under irradiation of 927 W / m². The ambient temperature T_{amb} reached 38.50 °C. The temperature is a function of the sunshine because the variations in the irradiance profile influence the temperature T_{chamb} in the same direction.



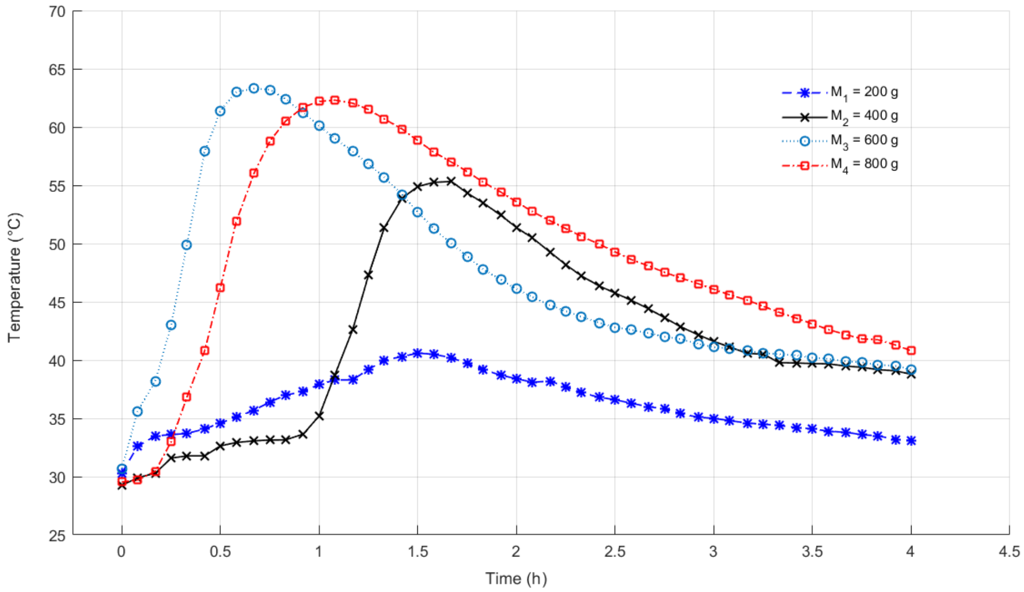
Figuere 4. Ambient and chamber temperatures and irradiance profile as a function of time.

II.2. Performance of the dryer with biomass supplying

During a test on the dryer with biomass supplying, the chamber temperature during the combustion of various quantities of coal varies, as in figure 5. The curves of this figure show that for each mass of the coal, the variation of the temperature in the dryer presents a maximum at some time. The temperature profile shows that the heat produced is a function of the mass of coal. A temperature of 63 °C was obtained after 0.58 h for the mass of 600 g, while for the mass of 800 g, the temperature reached 61.71 °C after 0.92 h of operation. However, for 200 g of charcoal, the temperature reached 40.6 °C, and for 400 g of charcoal, it is 58.33 °C and remained above 50 °C for one h.

For 600g of charcoal, the temperature increases rapidly and lasts 1.34h above 50 °C against 1.75h for the quantity of 800g.

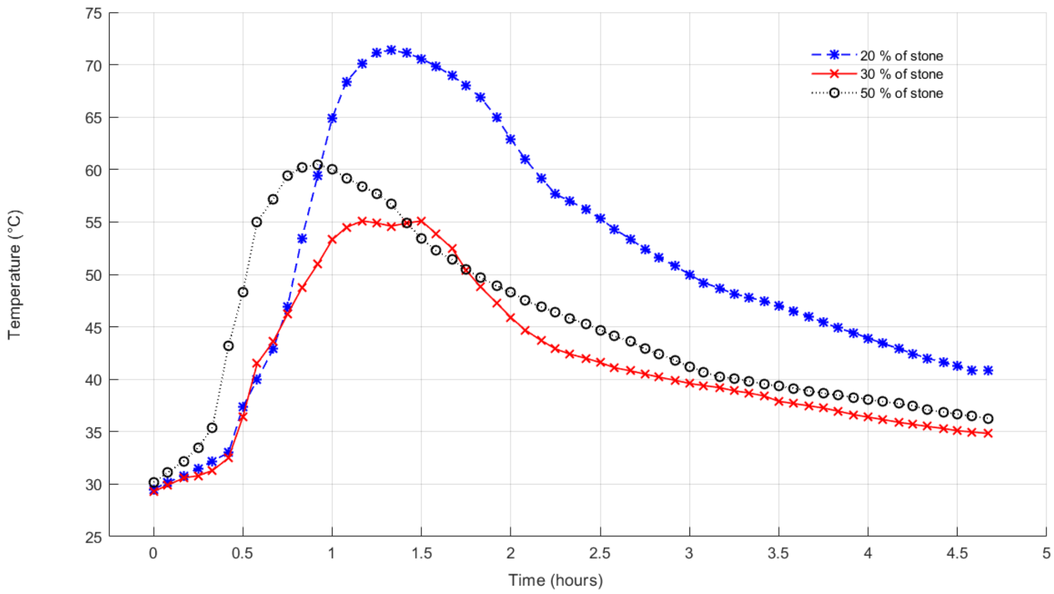
The best behavior of the dryer is obtained for 600 g of combustible considering the volume of the combustion chamber.



Figuere 5. Temperatures in the dryer for different charcoal mass.

II.3 Influence of energy storage in a biomass dryer

During experiments with biomass, various proportions of charcoal and pozzolan were used: first 80% charcoal or 600 g and 20% pumice stone or 120 g (blue curve), then 70% charcoal and 30% pumice stone (red curve) and finally 50% charcoal and 50% pumice stone (black curve). The chamber temperature during the combustion of various proportions of pumice stone varies as in figure 6.

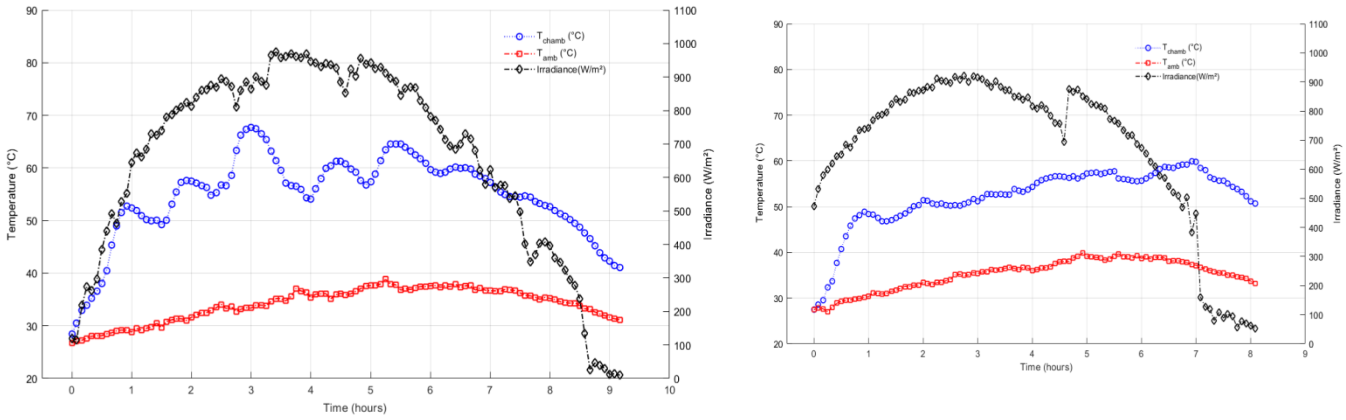


Figuere 6. Temperature profile of the chamber for different proportions of stone.

For 20% stone, the maximum temperature is 71.37 °C. We were able to have temperatures above 50 °C after 2 hours 05 minutes of operation. This shows that the stones have stored heat. The combustion has lasted 4 hours 40 minutes. For 30% of the stone, the maximum temperature reached is 64.28 °C. Temperatures above 50 °C were obtained after 1 hour 20 minutes of operation. The combustion has lasted 2 hours 40 minutes. Furthermore, for 50% of the stone, the maximum temperature reached is 60.02 °C. Temperatures above 50 °C were obtained after 1 hour 15 minutes of operation. The combustion lasted three hours 10 minutes. The best result is obtained for the proportions of 20% stone and 80% coal.

II.4. Performance of the Hybrid Biomass - Indirect Solar Dryer (HBISD) with and without storage

The dryer's performance obtained during tests with a solar collector and the biomass source are shown in figure 7a. The temperature in the chamber, $T_{chamb,}$ has reached 67.65 °C. The system's temperature is no longer a function of irradiation alone; it also depends on the heat produced by the fireplace. The temperature continues to rise even when the sun's radiation drops. The total amount of charcoal used up to 7.92 h is 2400 g.



a) b)

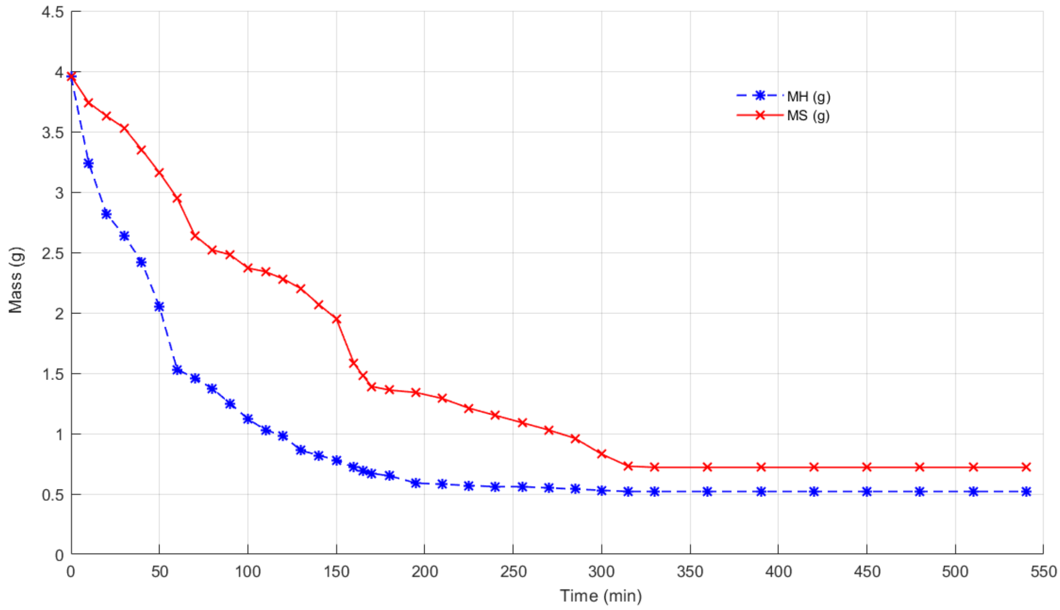
Figuere 7. Ambient and chamber temperatures and irradiance profile as a function of time: a) hybrid dryer without storage; b) hybrid dryer with storage.

Figure 7b shows the temperature obtained during the test with solar biomass and storage using pozzolan. The quantity of charcoal of 600g and the proportions of 20% stone and 80% charcoal were retained for further tests.

The temperature in the chamber, $T_{chamb,}$ reached 57.78 °C and had lasted more than 7 hours above 48 °C. The quantity of charcoal used is 1200 g, i.e., half the quantity used without pozzolan (2400 g). Less charcoal is used for almost the same run time and temperature.

II.5. Drying kinetics of the guava

The mass loss of different drying modes is shown in figure 15. MH represents the mass loss of drying in hybrid mode, MS the mass loss of drying in indirect solar mode. These mass losses decrease with the increase of the time and reach a constant value after a certain time, depending on the drying mode



Figuere 8. Guava drying kinetics.

In hybrid mode, the invariant mass was obtained after 3.75 h against seven hours in the indirect solar mode. Sekyere et al. (2016) obtained in the case of the indirect solar dryer the shortest drying time of 7 h compared to a drying time of 23 h for the drying mode under the solar.

Conclusion

The Hybrid Biomass - Indirect Solar Dryer (HBISD) with storage system was designed and fabricated using local materials. Its solar thermal collector has a surface area of 0.2 m², and the drying chamber has a volume of 0.402 m^3. The smoke chamber built-in aluminum sheet is separated from the drying chamber and thermally insulated in wood. A biomass source using charcoal and pozzolan was added to the indirect solar dryer to improve its performance. According to the volume of the fireplace chamber, the mass of 600 g of charcoal allows to reach chamber temperatures above 50 °C and during a long period compared to others charcoals mass. By adding various proportions of pozzolan (20, 30, or 50%) in the charcoal for storage, the proportion of 20% has given a higher chamber temperature (71.37 °C) that stays during a long period above 50 °C. The quantity of charcoal used during storage (1200 g) is less than that using in the hybrid dryer without pozzolan (2400 g) for the same run time and chamber temperature. This made it possible to save charcoal and improve the performance of the dryer.

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