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## Abstract

In response to changes that are taking place at the level of climatic variability and the increase in greenhouse gases produced by human activities at a local, regional and international level, plus the current dependence on fossil fuels, we must now act by replacing existing technologies with cleaner, safer and more innocuous ones. There is an urgent need to find new alternatives to support, with clean technologies, the productive processes of small and medium agricultural and agro-industrial producers in order to mitigate the effects of greenhouse gases. With that in mind, it is possible to help in the reduction of climate impact starting the change from the local, as well as improving production processes and their innocuousness in farms and small agro-industries. The objective of this work was to design, build and evaluate the implementation of solar thermal systems for the drying and dehydration of grains, seeds, fruits and other agricultural and agro-industrial products. The designed systems were active and passive, namely: thermosiphon and forced hybrid, with air and hot water, as well as with an auxiliary LP gas system. These systems have been able to supply more than 50% of the energy required by the drying and dehydration process of several products. The results have shown the efficiency of solar systems as an alternative resource of clean energy for production units in Costa Rica. These units are ready to be efficiently used, reducing the carbon footprint at the local level and improving their production processes, as well as the quality of their products.

**Keywords:** Carbon Footprint, Solar Drying and Processing, Solar Energy, Productivity.

**Acknowledgments:** The working group related to the use and systematization of solar systems in agricultural and agro-industrial production units, are grateful for the support received from the University Regionalization Program (PUR), the Project Management (DP) both belonging to the Vice-Rectory for Research and Extension (VIE) of the Costa Rica Institute of Technology (ITCR). We also appreciate the support received from the Ministry of Agriculture and Livestock and the Foundation for the Promotion and Promotion of Research and Transfer of Agricultural Technology of Costa Rica (FITTACORI), as well as the associations of producers and private companies that have supported this initiative and allowed us to be able to use the systems in their facilities.

## Introduction

Traditional ways to achieve the conservation of seeds, fruits, and other agricultural products over the years, have been related to the use of various linked processes, resulting in the reduction of microbial load, dehydration, and drying. These processes correspond to the incorporation of added value that is used with agricultural and agro-industrial products to provide longer life and conservation period.

The dehydration food industry constitutes a very important sector all over the world, according to Fito et al. (2016) and Eswara and Ramakrishnarao (2013) and it is important to empower small and medium producers in this industry.

Dehydration is understood as the operation where water is completely or partially removed from the product and this definition can be applied to solids, liquids or gases and serves to describe several unit operations such as evaporation, adsorption, and others (Babalis et al., 2007; Banchero, 2008).

Another aspect is the methods used to achieve dry, dehydrated or processed products by applying different types of energy, including the use of biomass, fossil fuel, electricity, and solar energy. There are several methods used including traditional and technical systems. Traditional sun-drying systems, although effective and historically used, have a series of disadvantages: they correspond to slow processes, they require large land extensions, they do not have adequate control of the process, the final products are obtained with very low sensory quality and they are not very innocuous (Berriz and Manuel Álvarez González, 2008; Bergues et al., 1996). The systems of artificially drying methods are more viable, fast and innocuous. For this reason, we have designed, built and evaluated those systems.

Since ancient times, it has been recognized that foods with the highest moisture content are the most perishable, in such a way that the control of the moisture content of a product is a tool for its conservation.

## Literature Review

The dehydration operation also entails an appreciable reduction in the weight and volume of the food that is dehydrated, thus achieving a significant reduction in transport and storage costs. Drying in unitary operations is "the extraction of moisture from a substance", that is, water that is contained in the solids is removed by means of artificial or natural methods (Ekechukwua and Nortonb, 1997; Moya et al., 2011; Espinoza, 2016; Treyball, 2016; FAO, 2018).

In drying by "artificial" methods controlled thermodynamic methods are used, where a certain percentage of moisture can be extracted, also controlling the properties of foods that determine their quality such as color, aroma, taste, rehydration capacity, life useful, etc. (Sogari, 1998; Tarigan et al., 2007; Fito et al., 2016; Machado et al., 2010).

The drying process is basically a mass transfer operation that occurs during the contact of the solid with the air; the water content found in the solid is transferred by evaporation to the gas; this occurs based on the difference in pressure between the vapor of the wet solid and the air (Costa, 2007; Yunus, 2007; Ferreira, 2009; Tiwari, 2016).

The mechanism of the drying process depends considerably on the way in which water is related to the solid: the more compact and molecularly linked the food is, the more difficult it will be to remove its moisture, so we can say that during drying the link of moisture with the material is altered.

In this process whose interaction is "solid-gas", the solid part will be considered as the wet material to be dehydrated and the gaseous part is the representation of the hot air used in the dehydration process. The phenomenon of thermal equilibrium that occurs in the drying of food is, in a few words, the following:

The wet solid enters the drying tunnel, where a stream of hot air will pass directly over the surface of the food; this will produce that the water that is as much in the surface as in the interior of the solid equals its temperature with the one of the air, evaporating and giving way to the process of dehydration.

Another of the objectives pursued with the dehydration of foods is the transformation of these into suitable raw materials for the mixing and formulation of new products.

## Dehydration Techniques in Agricultural Products

The dehydration can be carried out by different methods, among them mechanical and physical-chemical ones, namely: pressing; osmosis; centrifugation; lyophilization; freezing; absorption and surface evaporation. In our case we are going to stop in the latter because it is one of the most used methods, also called hot air dehydration (Hernández et al., 2010; Michalewicz et al., 2011).

The consumption of energy in the dehydration and drying of food and agricultural products is very important, and looking for solutions must reduce the cost of these processes. Among these solutions are the following:

a) The modification of dehydration processes and techniques and looking for the efficiency of industrial dehydrators in order to seek maximum energy efficiency.

b) Use of alternative energies. Of all the alternative energies, the use of waste or agricultural by-products used as fuels and solar energy seem to be the most viable (Busso et al., 1996; Busso and Sogari, 1997; Costa and Ferreira, 2007; MacManus et al., 2010; Espinoza, 2016, Fahim and Kang, 2016; FAO, 2018).

The different types of dryers are based on ways of transmitting heat using various sources of energy, which can be convection, conduction, and radiation.

In convection drying the heat is transferred to the solid that is drying or dehydrating by means of a stream of hot air that, in addition to transmitting the heat necessary for the evaporation of the water, is also the transport agent of the water vapor that is removed to the solid. In convection dryers, hot air is driven through the dryer by means of fans and the energy sources used to heat the air are quite varied.

## Dehydration Principle

Dehydration is based on the principles of psychrometry, which studies the thermodynamic properties of moist air and its effects. Humid air is defined as a mixture of dry air and water vapor and this is relative humidity. The natural condition of humid air is to saturate itself, in other words, to reach 100% relative humidity, therefore if the air has a humidity of 14, low relative humidity, when coming into contact with an object, food, fruit, seed, and grain, is bound to absorb its moisture and consequently dehydrate it. The maximum percentage of relative humidity that ensures proper preservation of food should be below eighteen percent. The parameters that allow desiccation are the inlet and outlet temperatures of the dehydration chamber, specific heat at constant pressure, enthalpy of the air at the inlet and outlet, mass flow, and mass of air present in the chamber for an instant. Its characteristics are mass, latent heat at medium temperature, relative humidity with which it enters and the desired humidity to be dehydrated.

## The Use of Solar Energy

Solar outdoor drying has been used since time immemorial for the drying of meat, fish, wood and other agricultural products as a means of conservation. Solar drying can also be indirect within hybrid systems (Fito et al., 2016).

In order to take advantage of the benefits of clean and renewable energy provided by the sun, in recent years solar dryers have been developed mainly for the conservation of agricultural and forestry products of different types and levels.

However, due to the variability of solar radiation during days in different countries, areas or regions, an auxiliary power source should always be used. In this way, solar energy can be used if the objective of the drying process can be coordinated with the specific characteristics of solar radiation. Therefore, the geographical location that determines the number of sunny days per year and the intensity of radiation in the different zones are those that will define the use of these systems and their applicability. This type of energy is also more suitable for drying processes where small energy demands are needed. An important aspect of the use of solar energy is its cost, durability over time, and profitability.

The drying of agricultural products can be direct or by convection or indirect or by conduction.

Direct, or convection dryers: These are characterized by using hot gases that come into direct contact with the wet solid to which they transmit heat by convection fundamentally, and which drag the produced vapors out of the dryer. The hot gases can be: air heated by steam, products of combustion, inert gases, steam overheated, and air heated by solar radiation.

In these types of dryers, the higher the fuel consumption is, the lower the residual moisture content of the final product. These types of dryers can be continuous or intermittent. For these dryers, there are two main types, oven or stove dryers and trays or closet dryers

Dried by conduction or indirect heat: In these dryers, the transmission of heat to the wet material takes place by conduction through a wall, usually metallic. The source of heat can be: by condensing water vapor, hot water, thermal oils, combustion gases, and electrical resistance. Indirect dryers allow solvent recovery and are suitable for drying at low pressures and in inert atmospheres, which makes them recommendable to dehydrate thermolabile or easily oxidizable products, being able to use agitation methods to ensure a better heat transmission and eliminate moisture gradients in the product. Like the direct ones, they can operate in continuous or intermittent mode (Busso et al., 1996; Kamaruzzaman, 2011).

Considering all of the above, our work was aimed at achieving adequate designs of dryers, dehydrators using solar energy.

## Methodology

The work began in February 2016, in the Northern Zone of Costa Rica, and is still ongoing. The interval of solar radiation in this area is between 1,500 – 1,900 KWh / $m^{2.}$

To better understand the development of the application of solar energy in the incorporation processes of added value to agricultural and agro-industrial production in rural conditions of Costa Rica (especially in drying and dehydration to achieve greater durability of seeds, fruits and other products), a comprehensive bibliographic search was made of the available international information related to the topic (Vega et al., 2005; Saravia et al., 2007; Sivipaucar et al., 2007; Orozco and Bedoya, 2007; Salas et al., 2008; Guía asit, 2010, Michalewicz et al., 2011; Queiroz et al., 2011; García et al., 2012; Martín, 2012; Iglesias et al., 2013; Nixon et al., 2013; Martinez et al., 2013; Taransum et al., 2015; Kamaruzzaman, 2011; Fahim and Kang, 2016; Mutombo and Glen, 2016; Comunidad de Madrid, 2016; Quintanar and Roa, 2017; Sreerag and Jithish, 2016).

Based on this review, we proceeded to design passive and active drying and dehydration prototypes, whose principle is mixed, that is by direct convection and indirectly by conduction and with an auxiliary system to guarantee the continuous level of solid–gas heat exchange.

In both of the prototypes of solar drying, solar energy is used to heat the air, water and to dry any food substance or product that is loaded into the treatment chamber.

The diagrams of the designs made to dry or dehydrate any agricultural product are presented. The equations that model the behavior of the dehydrator that best suit our work are:

Dehydration Energy:

The energy needed to dehydrate the fruit (kW).

$Qd = \dot{m}fp * Cv = \dot{m}a * Ca * (Ti - Ts)$

where "mfp" is the mass of water lost in the process (kg); "Cv", the latent heat of the water at medium temperature (kJ / kg); "Ma", the mass of the air at a given instant; "Ca", the specific air at constant pressure (kJ / kg * K); "Ti / Ts", temperature of entry and exit of air (0C).

- Mass of Lost Water:

Conditioned by the desired relative humidity

$(mfp)$. $mfp = m * \varphi i - \varphi s$ $100 - \varphi s$ (2.12)

where the mass of the object is represented by m; relative humidity on entering and leaving the process, defined by "φ".

- Absorption Power:

The amount of water vaporized per time defines the absorption power Pa expressed in kW.

$Pa = \dot{m}a * Ca * (Ti - Ts) = \dot{m}a * (hi - hs)$

ma: the mass flow of air; hi: enthalpy of entering the system; hs: enthalpy of system output.

The energy consumption needed to eliminate one kg of water is 1,000 kcal. This amount is composed as follows (FAO, 2018).

| | |
|---|---|
| The heat required for the evaporation of 1 kg of water | 600 kcal |
| Loss from the sensible heat that goes into the used air | 300-320 cal |
| Losses of heat through conduction, radiation, and convention towards the outside | 30 kcal |
| Loss from the heat transported by the grain | 80 kcal |
| Total | 1,010-1,030 kcal |

The value of 600 kcal/kg of water cannot be diminished in any way since it is the minimum heat required to evaporate the water.

To implement the solar drying systems in the Northern Region of the country, it was necessary to know the working conditions of the producers in the area to adapt each of these systems to their needs. Therefore, it began with the study of the possible options of application of dryers that they should use in their production chain of different products such as cocoa, beans, and fruits to achieve greater efficiency, durability, and quality.

Based on the previous work, several solar dryers were designed, which were as follows:

1. Passive thermal solar dryer or natural circulation, prototype No 1.
2. Hybrid active solar thermal dryer with forced circulation, with a gas back, prototype No 2.
3. Active hybrid solar thermal dryer with forced circulation, commercial system models, with gas back, I and II.

For the evaluation of the equipment, hourly temperatures were measured for several months during the day. Several agricultural products were dehydrated, including coffee, beans, corn, cocoa, pineapple, banana, turmeric, sweet potato, and cassava. Here, only the results of the dehydration of beans, corn, and cocoa are shown.

The rest of the products had a behavior similar to the above mentioned. The data was recorded through a computerized system.

## Results and Discussion

Based on the work carried out in designing, constructing and preliminary evaluation, we reviewed each of them as follows:

### *Passive Solar Thermal Dryer or Natural Circulation, Prototype No 1*

It is located in the Regional Headquarters of the Costa Rica Institute of Technology (ITCR), San Carlos Campus, Santa Clara, in the province of Alajuela.

This passive system has two hot air collectors, one in the bottom solar collector flat 1 of the system and another in the upper solar collector flat 2.

The flat solar collector contains a manual control window that regulates the air intake (Ti) to the treatment or drying chamber. The chamber contains a group of nine trays with a capacity of 100-250 kg. This chamber, in turn, has another manual upper mobile window, which allows the opening or closing of the hot air outlet (Tf), to achieve the passage of air naturally by density difference. Collector 2 is located in the upper part of the treatment chamber (Figure 1).

The operation of this dryer is natural and does not need any additional energy to achieve the drying of the products. The principle of operation is that of a thermos-syphon, whereby the movement of air is achieved through the temperature difference in the lower part of the collector, where the cold air enters and rises through the inclination of the same and entering the treatment chamber, which also has another solar collector in the upper part.

The system has three temperature control thermometers arranged as follows: two in the treatment chamber, one in the lower part, one in the upper part, and another in the flat solar collector. The parts and dimensions of this system can be seen in Table 1. The costs of the whole system in dollars are shown in Table 2.

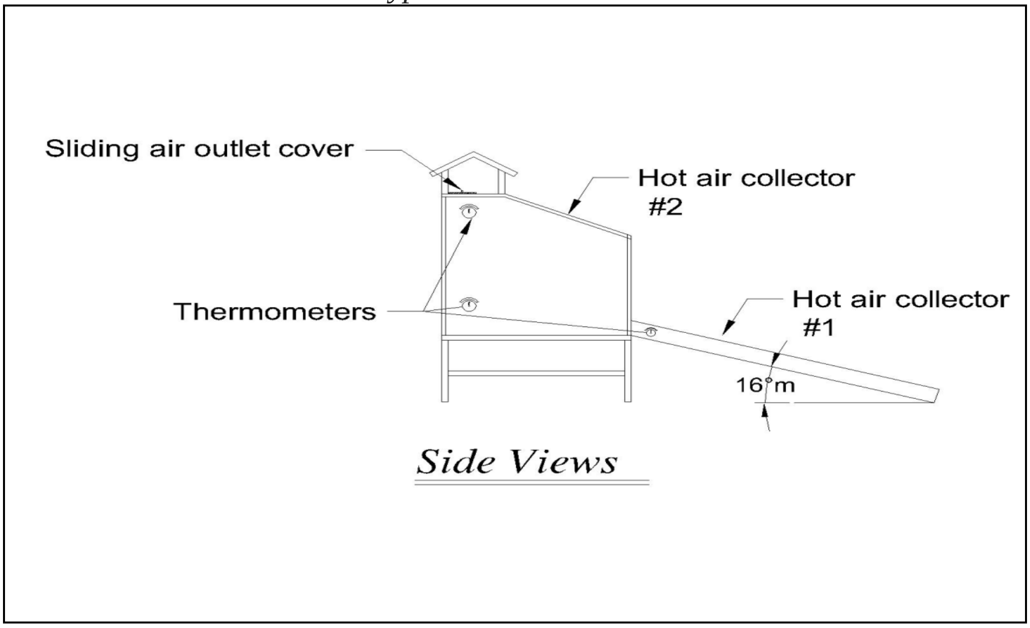
**Table 1.** *Component Parts and Dimensions of the Passive Thermal Solar Dryer or Natural Circulation*

| Parts of the system/structure | Solar collector 1 | Solar collector 2 | System support | Treatment chamber |
|---|---|---|---|---|
| Dimensions | 1.02 x 2.45 m | 1 x1.5 x1 m | 1 x1.5 x 0.65 m | 1 x 1.5 x 1.5 m |
| Area of the collectors | 2.50 $m^2$ | 1.5 $m^2$ | | |
| Dryer volume | | | | 2.25 $m^3$ |
| Drying capacity/batch | | | | 250 kg |
| Control thermometers | 1 | | | 2 |

**Table 2.** *General Costs of the Passive Solar Dryer*

| List of Materials for Portable Passive Solar Dryer | | Estimated total price USD |
|---|---|---|
| Total materials | | $ 2,322.98 |
| Basic equipment | | |
| 3 | Bimetallic thermometer 0/100 ° C. | $ 486.95 |
| Total materials and equipment | | $ 2,775.15 |
| Construction and installation | | |
| Total construction and installation | | $ 2,581.83 |
| Grand Total | | $ 5,357.48 |

**Figure 1.** *Treatment Chamber and Two Solar Collectors, with the Treatment Chamber and the Base. Prototype No 1*




Drying Tests in the Passive Dryer

To evaluate the performance of the passive solar dryer, drying and temperature measurement tests were carried out and three products were dried: cocoa, beans, and corn. The drying curves of corn and beans are shown in Figure 1a. The best-fit curves for corn and beans are shown in Figures 1b and 1c. The dryer temperatures were measured, as shown in Figures 2 and 2a. Humidity curves:

**Figure 1a.** *Changes in the Percentage of Moisture Content of Dried Corn and Bean Seeds in a Passive Solar Dryer in Santa Clara de San Carlos*

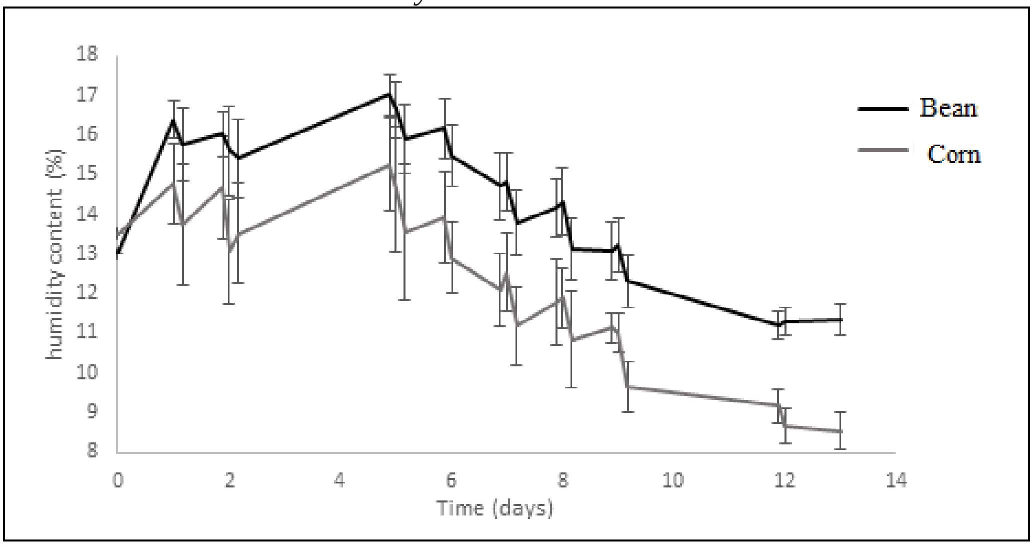


**Figure 1b.** *The Best-fit Equation for Corn Drying Curve in a Passive Dryer, Santa Clara de San Carlos*

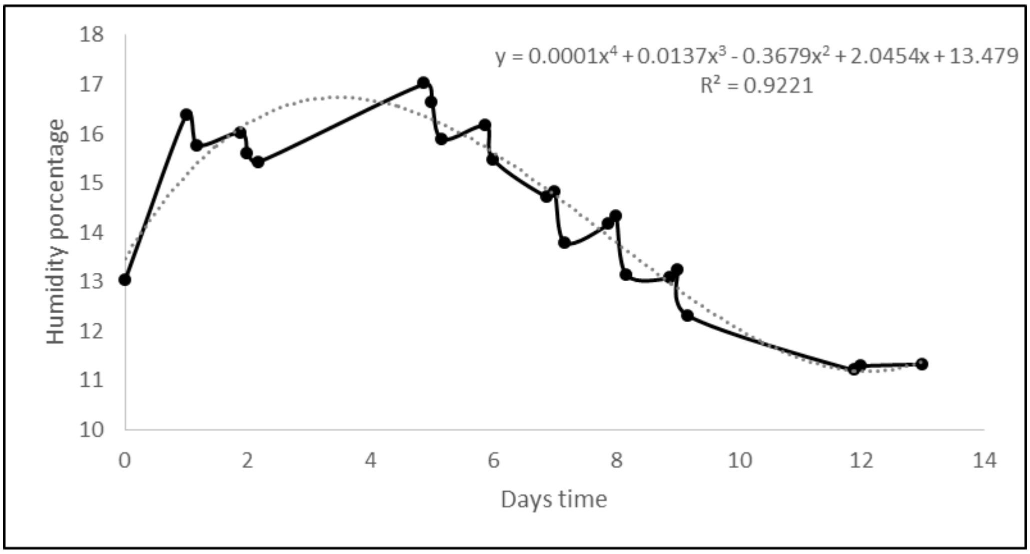
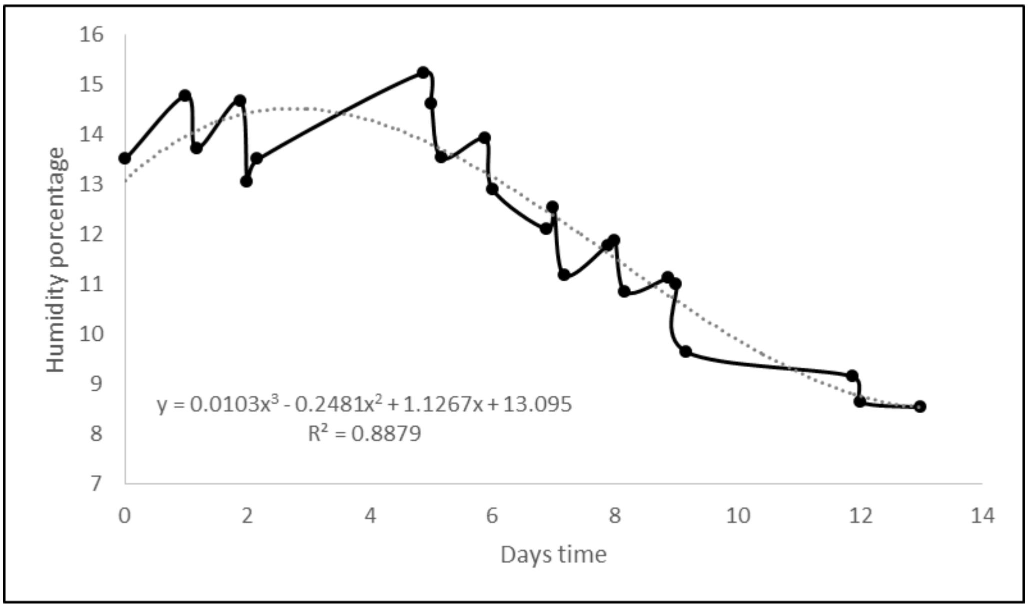



**Figure 1c.** *The Equation of the Best Fit for the Drying Curve of Bean in a Passive Dryer, Santa Clara de San Carlos*



Passive Solar System Temperature

**Figure 2.** *Average, Minimum and Maximum Temperatures for the Passive Dryer in Santa Clara de San Carlos, Costa Rica, for the Months of August to October 2017*

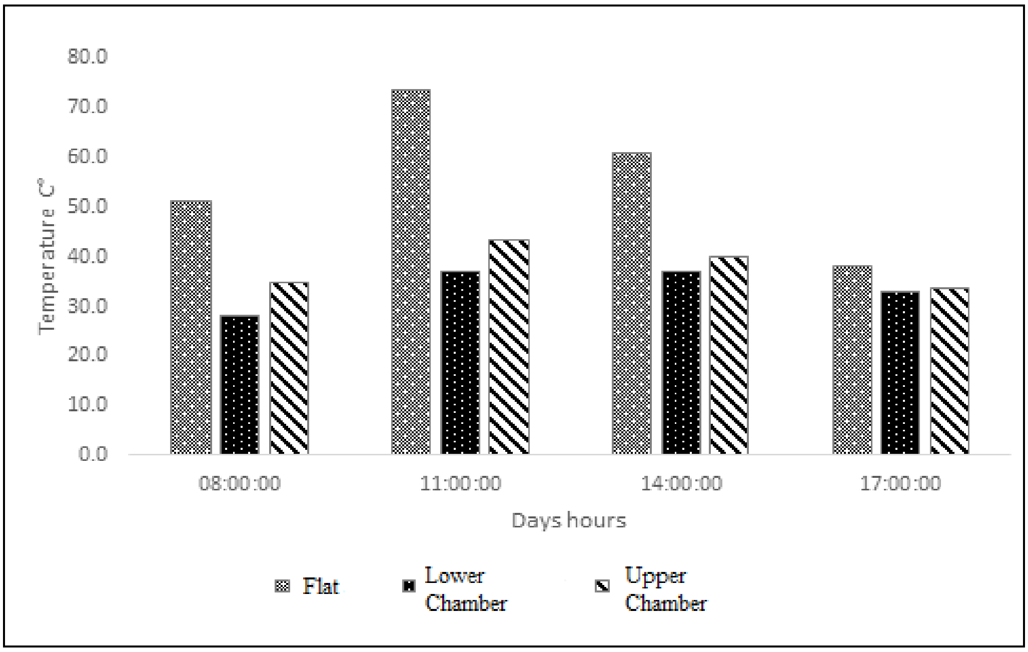
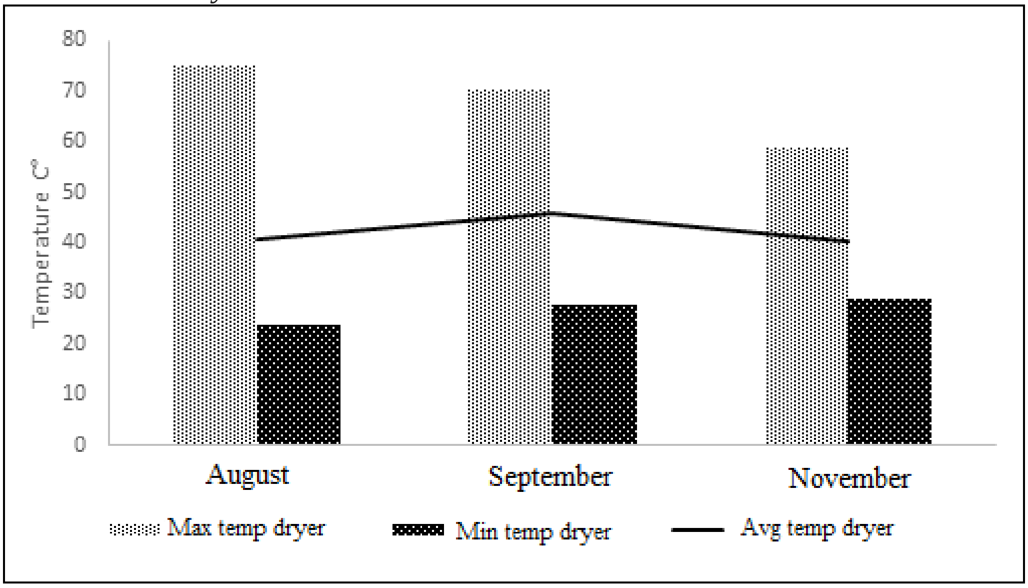



**Figure 2a.** *Temperature Fluctuation per Month in the Drying Chamber of a Passive Solar Dryer in Santa Clara de San Carlos*




The temperature varied slightly from one month to another, during the month of October there are lower temperatures. It is important to take into account the time of year in which the product will be put to dry as well as the available solar radiation and the temperatures that are achieved Table 3.

**Table 3.** *Maximum Temperatures Recorded with Integrated Thermometers*

| Maximum temperatures (C°) | Time | | | |
|---|---|---|---|---|
| | 8:00 | 11:00 | 14:00 | 17:00 |
| Collector | 100 | 100 | 99 | 70 |
| Lower Chamber | 40 | 45 | 44 | 45 |
| Upper Chamber | 53 | 52 | 49 | 46 |

*Hybrid Solar Thermal Dryer with Forced Circulation, Prototype 2*

Located in San Rafael de Alajuela in the capital San José, it was designed by the Technological Institute of Costa Rica and a private company.

The hybrid thermal forced hybrid dryer consists of several integrated modules that, when joined together, achieve an optimal drying of the agricultural products that are to be processed (Figure 3).

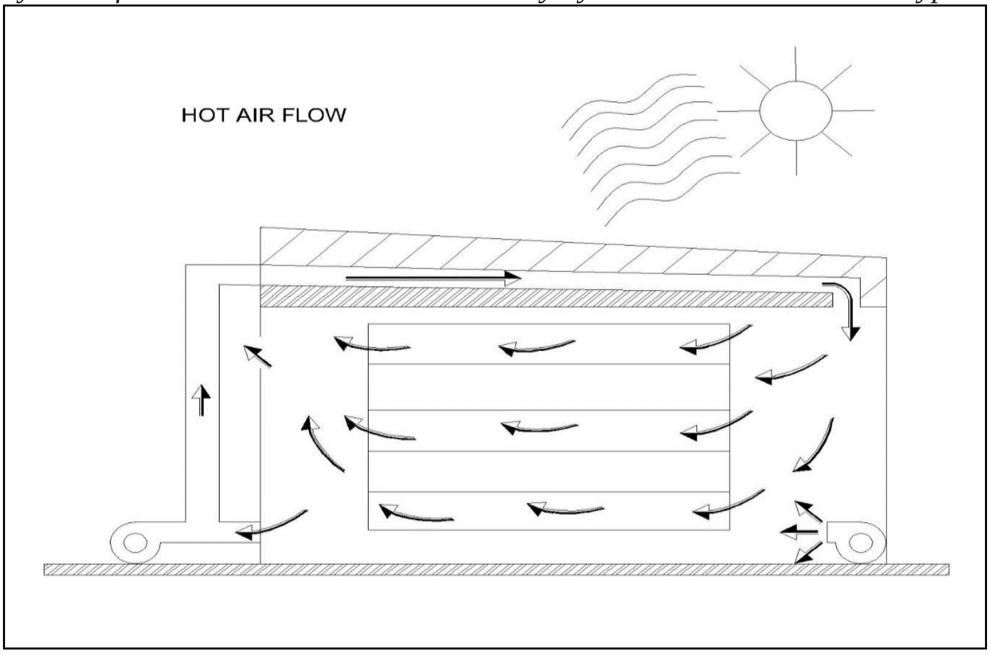
The equipment consists of a forced solar system for air heating, which is formed by an air recirculation pump, three hot air collectors and a system of conduction and hot air output, which uses the initial value of the temperature of the air. Initial air (Ti) and injects it with a final value (Tf) whose air flow is shown in Figure 4.

It has a forced solar system of hot water, with three solar thermal collectors, a system of pipes that conduct water at room temperature (Ti) and store it in the tank with temperature (Tf) Figure 3 and Table 4. Two pumps for the circulation and recirculation of the water at room temperature and the hot water, a thermostat, a temperature and humidity control system, an auxiliary system with LP gas, to homogenize the temperature, when necessary, depending on the local radiation. The hot water is circulated through a radiator that achieves the convection of the temperature inside the chamber. Hot water can be used during the night or day when solar radiation is not enough. This prototype is known as a forced hybrid thermal solar dryer since it has air, water, and LP gas, the gas heating system comes into operation to generate the necessary temperature and ensure uniform drying through a thermal control system or thermostat, by convection and driving. The solar dryer is equipped with a data control system that records the temperature and humidity of different points of the dryer for optimum performance. The circulation of hot air can be seen in Figure 4.

**Table 4.** *Component Parts and Dimensions*

| Parts of the system/structure | No additional equipment | Three solar collectors for hot air | Two solar collectors for water Control radiator | Control radiator | Treatment or drying chamber |
|---|---|---|---|---|---|
| Dimensions | | 3.2 x 1.6 m | 1.45 x 0.8 m | 2.80 x 1.5 m | 3.6 x 1.9x 1.8 m |
| Area | | 15.36 $m^2$ | 2.32 $m^2$ | 4.2 $m^2$ | 6.84 $m^2$ |
| Volume | | | | | 12.31 $m^3$ |
| Drying capacity/batch | | | | | 500-650 kg / cargo |
| Thermometers | 4 | | | | |
| Fans | 2 | | | | |
| Pumps | 3 | | | | |
| Thermostat | 1 | | | | |
| Data Logger | 1 | | | | |

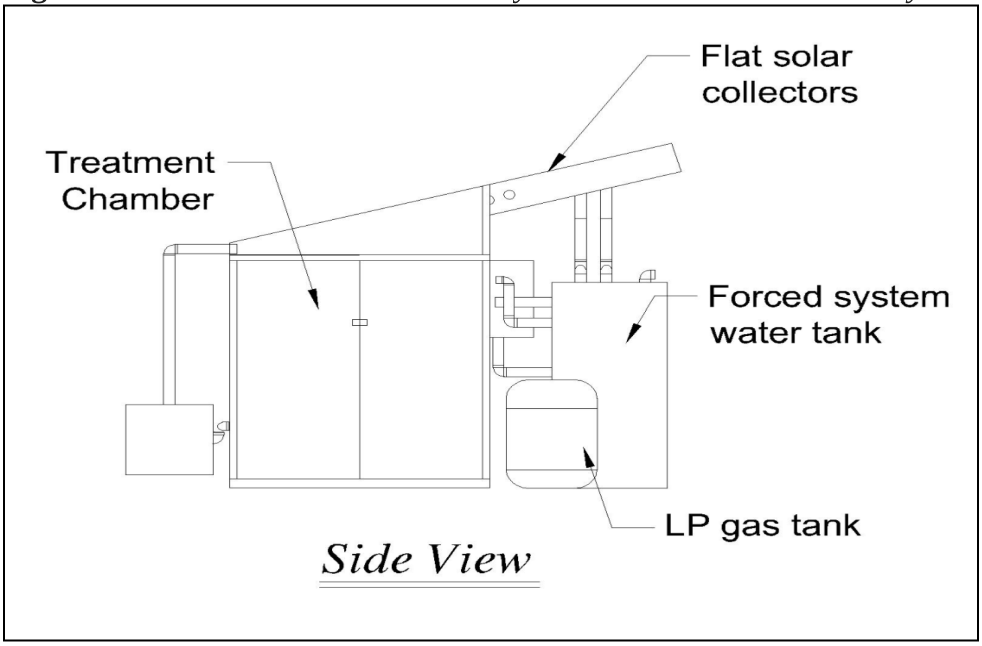
**Figure 3.** *Hybrid Forced Active Solar Thermal Dryer, with a Forced Solar System of Water and Hot Air and Auxiliary System with LP Gas. Prototype 2*




Two more were designed based on the results obtained with this experimental prototype.

One is located in San Rafael de Guatuso, in the Katira Cocoa Environmental Producers Association in the SME SIBAELI and the other in Santa Clara de San Carlos in the Headquarters of the Technological Institute of Costa Rica, both in the North zone.

**Figure 4.** *Hot Air Flow in the Forced Hybrid Active Thermal Solar Dryer*




*Active Hybrid Solar Thermal Dryer with Forced Circulation, Prototype I and II*

This prototype was built on the basis of the results of the previous one, and is located in San Rafael of Guatuso, Katira, in a small cocoa processing company to produce chocolate and consists of the same parts as the previous one, but enlarged, to achieve greater solar heating area (Figure 5).

It has a forced solar system for air heating, which is formed by an air recirculation pump, six hot air collectors next to the system, with a hot air inlet and outlet conduction system, with an initial value of the air temperature (Ti) and injects it with a final value (Tf) Figures 5 and 6, prototype I is shown and in Figure 7 Prototype II is shown. It also has a forced hot water solar system, with three solar thermal collectors, a system of pipes that conduct the water at room temperature (Ti) and store it in the tank with temperature (Tf). Two pumps for the circulation and recirculation of water at room temperature and hot water, a thermostat, a temperature and humidity control system (data logger), an auxiliary system with LP gas, to homogenize the temperature, when necessary, depending on the local radiation. The component parts of the system, as well as their dimensions, can be seen in Table 5. A radiator that achieves the convection of the temperature inside the treatment chamber circulates hot water. This prototype is known as a forced hybrid thermal solar dryer since it has air, water, and LP gas for when solar energy is not enough, the gas heating system comes into operation to generate the necessary temperature and ensure a uniform drying through a thermal control system or thermostat, by convection and conduction. The forced hybrid solar dryer is equipped with a data control system that records the temperature of different points of the dryer for optimal operation.

**Figure 5.** *Hybrid Forced Active Solar Dryer, with a Forced Solar System of Water and Hot Air and Auxiliary System with LP Gas from San Rafael de Guatuso and the Costa Rica Institute of Technology (ITCR) Prototype No. I*

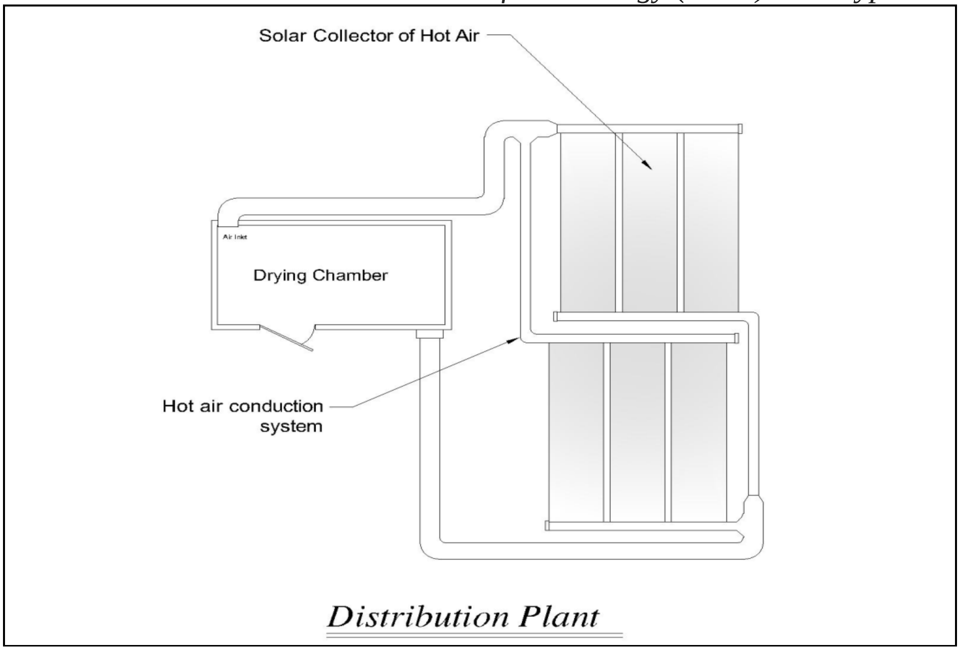



**Figure 6.** *Hot Air Flow of the Prototype Thermal Solar Dryer No I*

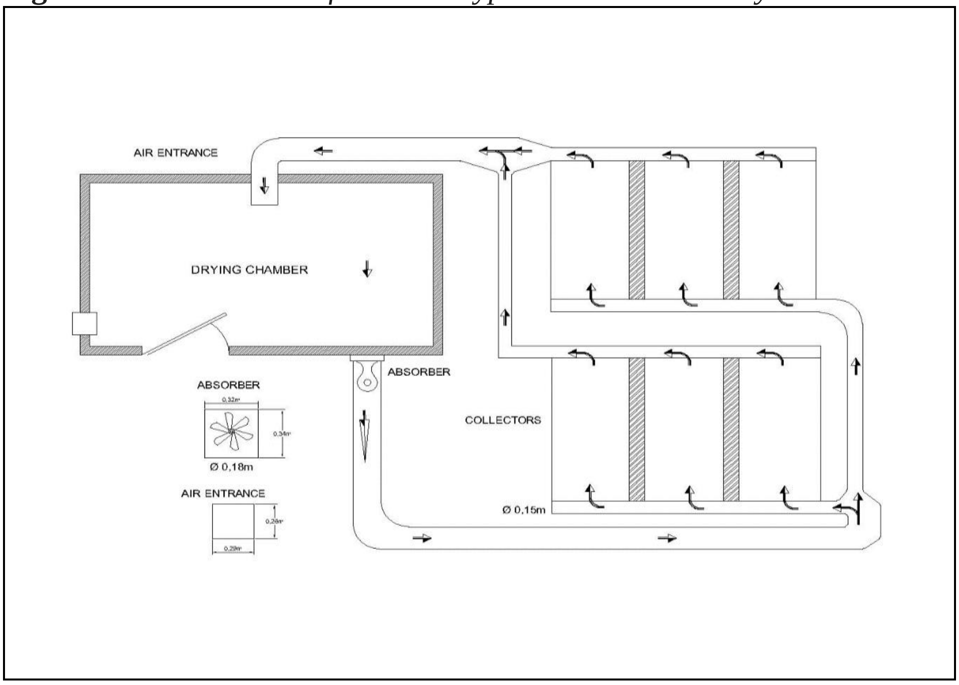
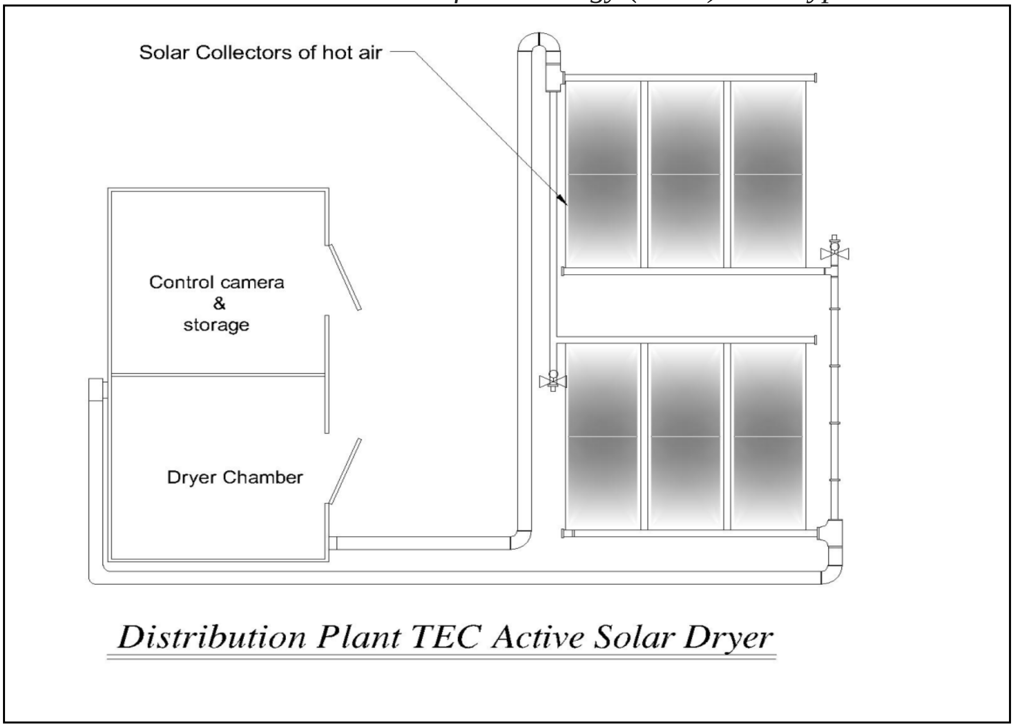


**Figure 7.** *Hybrid Forced Active Solar Dryer, with a Forced Solar System of Water and Hot Air and Auxiliary System with LP Gas from San Rafael de Guatuso and Costa Rica Institute of Technology (ITCR) Prototype No. II*




The component parts and their dimensions can be seen in Table 5.

**Table 5.** *Components and Dimensions. Solar Thermal System for Forced Water Heating*

| Parts of the system/structure | No additional equipment | Six solar collectors for hot air | Three solar collectors for water | Water tank | Radiator | Treatment chamber |
|---|---|---|---|---|---|---|
| Dimensions | | 1.06 x 2.95 m | 1.0 x 2.10 m | | 2.5 x 1.5 m | 3 x 2.88 m |
| Area | | 18.76 m$^2$ | 2.10 m$^2$ | | 7.5 m$^2$ | 8.64 m$^2$ |
| Volume | | | | 200 l | | 3 x 2.88 x 1.98 17.10 m$^3$ |
| Drying capacity / batch | | | | | | 750 - 1,500 kg / carga |
| Radiator | 1 | | | | | |
| Fans | 2 | | | | | |
| Pumps | 3 | | | | | |
| Thermostat | 1 | | | | | |
| Datalogger | 1 | | | | | |

The cost of the forced hybrid solar system of drying and dehydration with air and hot water and LP gas can be observed in Tables 6, 6a, 6b, 6c and 6d.

**Table 6.** *System Components and Dimensions*

| Units | Description | Value | Observations |
|---|---|---|---|
| 1 | Vertical pressurized tank for hot water.<br>An indirect system with an internal heat exchanger coil.<br>Built-in electric backrest<br>a) | | This is a complete integrated syste |
| 3 | Flat solar collectors<br>• High-efficiency selective absorber<br>• AL6063-T5 anodized aluminum frame<br>• 3.2 mm thick solar tempered glass<br>Aluminum background with polyurethane insulation and stone wool.<br>b) | | |
| 1 | Hydraulic group | | |
| 15 m | Long line pipe<br>The double insulated pipe between collectors and tank<br>Sensor cable | | |
| | The total cost of this system | **$ 4,200.00** | |

**Table 6a.** *Additional Systems Used Inside the Dryer*

| Units | Description | Value | Observations |
|---|---|---|---|
| 1 | Electrical installation and lighting | $ 300.00 | Lighting of the cameras |
| 1 | RC Recirculation in the drying system Pump with a timer | $ 460.00 | For day/night circulation of hot water |
| 1 | Gas backup<br>• Pass burner Model RTS 1316<br>• Capacity: 13 l / min. Delta T 250 K<br>c) | $ 1,204.00 | Sistema híbrido |
| 1 | Data logger (forced system) | $ 500.00 | |
| 1 | Radiator (2 parts) | $ 500.00 | |
| 2 | Two special structures for mounting flat floor collectors and photovoltaic panels | $ 1,200.00 | |
| 1 | Installation of the solar system and its additional components | $ 1,655.00 | |
| 1 | Dehumidifier of 28 $m^3$ | $ 201.00 | |
| Total | | **$ 6,020.00** | |

**Table 6b.** *Forced Air Heating System*

| Units | Description | Value | Observations |
|---|---|---|---|
| 6 | Solar absorber for the solar treatment chamber | $ 4,120.00 | |
| 2 | Pumps / Fan for forced air 1,200-1,500 m3 / ft | $ 600.00 | |
| 1 | Special metallic pipes for installation | $ 300.00 | |
| 1 | External pipe insulation system | $ 350.00 | |
| 1 | Assembly and installation | $ 1,120.00 | |
| Total | | **$ 6,490.00** | |

**Table 6c.** *A Shelf of Trays for Drying*

| Units | Description | Value | Observations |
|---|---|---|---|
| 2 | Shelves for storage of trays for drying<br>Height x width x length: 1.80 m x 0.90 m x 0.75 m.<br>The separation between trays 0.15 m<br><br>Number of trays 24 | $ 1,206.00<br><br><br><br>$ 2,275.80 | |
| Total | | **$ 3,481.80** | |

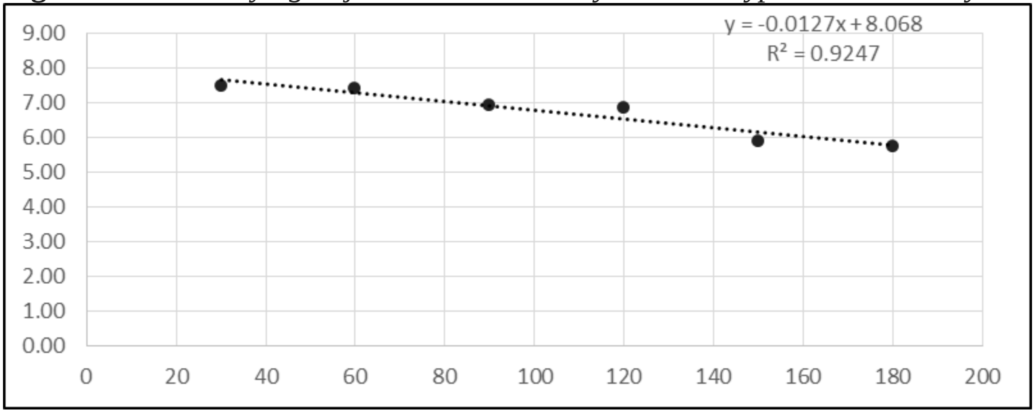
**Table 6d.** *Drying Treatment Chamber*

| Units | Description | Value | Observations |
|---|---|---|---|
| 1 | Fourth refrigerator with a waterproof roof<br>Acoustic thermo-panel of 6.00 m long x 2.975 m wide x 1.98 m high and 50 mm thick with dividing wall and 2 hinged doors of 1.10 m x 2 m high.<br>Ceiling panel for room 4.00 m long x 2.975 wide 30 mm thick<br>Includes profiles, angles, sealants, screws, and<br>Installation | $ 8,492.00 | |
| 1 | Transportation, installation, and turnkey | $ 1,034.00 | |
| Total | | **$ 9,526.00** | |
| General total | | **$ 29,717.00** | |

The advantages of these types of solar thermal dryers are: products with better sensory quality are obtained with a lower microbiological load (greater manageability of the products), the process is shorter and more efficient, drying is controlled better by being able to control the variables of humidity and temperature, the investment can be recovered in a period of 3-5 years with a system durability of 25-30 years of use. It helps reduce the local balance of greenhouse gases, since firewood or fossil fuels are replaced to generate energy, by the radiant energy of the sun.

The results in the thermal prototype hybrid solar dryer I are shown in Figure 8 and the temperatures achieved in Figure 9.

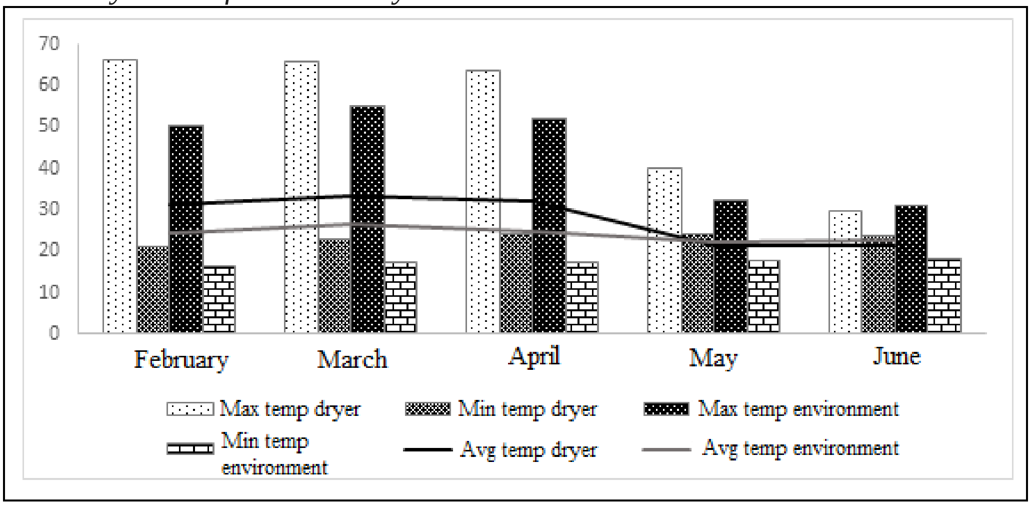
**Figure 8.** *Cocoa Drying Adjustment Curve in Hybrid Prototype No I Solar Dryer*




## System Temperature

The hybrid drying system has maximum temperatures of up to 66 ° C with the forced heating system for the months that the forced heating system remained on. The temperatures increase considerably with respect to the ambient temperature. The ideal temperatures for grain drying range between 35 and 65 degrees depending on the type of seed used, so it is important to note that, as indicated in the literature, the drying time increases with the high temperatures due to radiation.

**Figure 9.** *Maximum and Minimum Temperatures for the Prototype Hybrid Active Solar Dryer No 2 from February 2017 to June 2017*



## Conclusions

The four prototypes designed, constructed and evaluated managed to dry or dehydrate agricultural or agro-industrial products subjected to the action of these systems efficiently and in less than half the time of traditional systems.

## Recommendations

Work should continue on the data recording of these systems, as well as new designs based on the needs of producers and small and medium enterprises.

## References


Babalis, S.; Papanikolaou E.; Belessiotis, V. 2007. Investigation of the solar energy utilization for meeting part of the thermal demands of agricultural-product mechanical dryers. Solar & Energy Systems Lab, NCSR “Demokritos” 153 10 Ag. Paraskevi Attikis – Greece. Proceedings of ISES Solar World Congress 2007: Solar Energy and Human Settlement.

Banchero, L.; Carballo, S.; Telesca J. 2008. Manual de secado solar de especies medicinales y aromáticas para predios familiares. [Manual of solar drying of medicinal and aromatic species for family farms]. INIA - DIGEGRA - MGAP ISBN: 978-9974-563-49-0 Editado por la Unidad de Comunicación y Transferencia de Tecnología del INIA Andes 1365, Piso 12. Montevideo - Uruguay http://www.inia.org.uy.

Bergues, R.; Bèrriz, P. L.; Griñán, V. P. 1996. Generalización de secadores solares directos en Cuba. Análisis numérico de sus tendencias actuales. [Generalization of direct solar dryers in Cuba. Numerical analysis of your current trends]. DELOS. Revista Desarrollo Local Sostenible. Vol 3, Nº 8. Cuba.

Bérriz, P. L. and Manuel Álvarez González, A. M. 2008 . Manual para el cálculo y diseño de calentadores solares. [Manual for the calculation and design of solar heaters]. Editorial CUBASOLAR. calle 20 no. 4113, esq. a 47, Miramar, Playa, Ciudad de la Habana, Cuba. http://www.cubasolar.cu. ISBN 978-959-7113-36-2.

Busso, A.; Aeberhard, A.; G. Figueredo, G.; Martina, P.; Cocca, V. 1996. Optimizacion de un secadero solar por convección natural: análisis del colector solar de aire. [Optimization of a solar dryer by natural convection: analysis of the solar collector of air]. Dpto. de Termodinámica - Facultad de Ingeniería - UNNE - Av. Las Heras 727 - 3500 Resistencia - Chaco - Argentina.

Busso, A. and Sogari, N. 1997. Secado solar de productos horticolas en el nordeste Argentino. [Solar drying of horticultural products in the Argentine northeast]. FACENA, Universidad Nacional del Nordeste - UNNE Campus Libertad, Av. Libertad 5600, 3400 Corrientes – Argentina.

Comunidad de Madrid. 2016. Guía sobre energía solar térmica. [Guide on solar thermal energy]. www.madrid.org.

Costa A. R. and Ferreira S. R. 2007. Sistema de Secado Solar para Frutos Tropicales. [Drying Solar System for Tropical Fruits]. Información Tecnológica-Vol. 18 N°4-pág.: 49-58. ALIMENTOS Y AGROQUÍMICA.

Ekechukwua O. V. and Nortonb. B. 1997. Drying systems II: an overview of solar drying technology. Review of solar-energy Energy Conversion & Management. Energy Research Centre, University of Nigeria, Nsukka, Nigeria.

Espinoza S. J. 2016. Innovación en el deshidratado solar [Innovation on solar dehydrator]. Revista chilena de ingeniería, vol. 24. Número Especial, 2016, pp. 72-80. Chile.

Eswara, A. and Ramakrishnarao. J. 2013. Solar energy in food processing—a critical appraisal. Food Science of Technology. 2013 Apr; 50(2): 209-227. Published online 2012 Jun 6.: 10.1007/s13197-012-0739-3.

Fahim, U. and Kang, M. 2016. Impact of drying method of figs with small-scale flat-plate solar collector. World Journal of Engineering, Vol. 13 Iss 5 pp. 407-412. Downloaded by Instituto Tecnologico de Costa Rica At 20:25 30 January.

FAO. Capitulo IX - Secado de diversos granos. [Drying of various grains]. http://www.fao.org/docrep/X5028S/X5028S0e.htm. Recuperado el día 13 de marzo del 2018.

Ferreira S. R. and Costa, A. R. 2009. Parámetros de Transferencia de Materia en el Secado de Frutas. [Mass Transfer Parameters in Fruit Drying]. Versión On-line ISSN 0718-0764.Inf. tecnol. v.20 n.2 La Serena 2009. http://dx.doi.org/10.4067/S0718-0764200 9000200012. Información Tecnológica-Vol. 20 Nº2-pág.: 89-104 doi:10.1612/inf.tecnol.4034it.08.INGENIERIA EN ALIMENTOS

Fito M. P.; Andrés G. A.; Barat J. M.; Albors S. A. M. 2016. Introducción al secado de alimentos por aire caliente. [Introduction to drying food by hot air]. EDITORIAL UNIVERSITAT POLITÈCNICA DE VALÈNCIA. ISBN: 978-84-9705-025-8. España.

García, E. L.; Mejía M. F.; Mejía D. J.; Valencia, A. C. 2012. Diseño y construcción de un deshidratador solar de frutos tropicales. [Design and building of solar dryer equipment for tropical fruits]. AVANCES Investigación en Ingeniería Vol. 9 - No. 2 (2012).

Guía ASIT de la energía solar térmica. 2010.

Hernández R. J.; Martínez V. O.; Quinto D. P.; Cuevas D. J.; Acosta O. R.; Aguilar J. O. 2010. SECADO DE CHILE HABANERO CON ENERGÍA SOLAR. [DRYING OF CHILE HABANERO WITH SOLAR ENERGY]. Revista Iberoamericana de Tecnología Postcosecha, vol. 10, núm. 2, pp. 120-127 Asociación Iberoamericana de Tecnología Postcosecha, S.C. Hermosillo, México.

Iglesias Ferrer, Jesús M.; Morales Salas, Joel. 2013. Dimensionado de un sistema térmico solar mediante simulación y su validación energética. [Dimensioning of a solar thermal system through simulation and its energy validation]. Ingeniería Energética, vol. XXXIV, núm. 1, enero-abril, pp. 56-65. Instituto Superior Politécnico José Antonio Echeverría La Habana, Cuba.

Kamaruzzaman S. 2011. Report on The Solar Dryers and Solar Drying Technology and Design Prepared by Project: TF/CMB/04/001. Report on The Solar Dryers and Solar Drying Technology and Design Prepared by UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria.

Machado A. V.; Oliveira, E. L.; Santos E. S.; Oliveira, J. A. 2010. Estudio del Secado de Anacardo (Anacardium occidentale L.) mediante Secador Solar de Radiación Directa. (Cashew-nut (Anacardium occidentale L.) [Study of Cashew Drying (Anacardium occidentale L.) by Direct Radiation Solar Dryer.]Drying Study Using a Solar Dryer with Direct Radiation).Versión On-line ISSN 0718-0764.Inf. tecnol. v.21 n.1 La Serena 2010. http://dx.doi.org/10.4067/S0718-07642010000100006. Información Tecnológica-Vol. 21 Nº1-2010, pág.: 31-37. doi:10.1612/inf.tecnol.4137it.08.ENER GIA Y MEDIO AMBIENTE.

MacManus Ch. N.; Ogunlowo, A. S.; Olukunle, O. J. 2010. Cocoa bean (Theobroma cacao l.) drying kinetics, CHILEANJAR. Chilean Journal of Agricultural Research. 70(4):633-639 (OCTOBER-DECEMBER).

Martín, Y. C. 2012. Colectores solares de aire para el secado de maíz. [Solar air collectors for drying corn]. Universidad Carlos III de Madrid. Repositorio institucional. PROYECTO FIN DE CARRERA INGENIERÍA TÉCNICA INDUSTRIAL – MECÁNICA. e-Archivo http://e-archivo.uc3m.es.

Martínez, E. P.; Noceto, F.; Rodrigo, A. S. 2013. Manual Técnico de Energía Solar. [Solar Energy Technical Manual] Térmica Volumen II: Aspectos Técnicos y Normativos .2013 Publicación electrónica: Facultad de Ingenieráa, Universidad de la República. https://creativecommons.org/licenses/by-nc-nd/3.0/.

Michalewicz, J. S.; Henriquez, J. R.; Charamba, J. C. 2011. Secado de Cajuil (anacardium occidentale l.): [Dried of Cajuil (anacardium occidentale l.)] Estudio Experimental y Modelado de la Cinética de Secado. Información Tecnológica Vol. 22(6), 63-74 (2011) doi: 10.4067/S0718-07642011000600007.

Moya, R.; González, Prevez, P. L.; Sheyla, A. S.; José Guzmán, J.; Bello, M. 2011. El uso de la energía solar para la deshidratación de frutas y vegetales. Instituto de Investigaciones en Fruticultura Tropical. [The use of solar energy for the dehydration of fruits and vegetables. Institute of Tropical Fruit Research.] Ave. 7ma No. 3005 e/ 30 y 32. Miramar. Playa. La Habana. Cuba. Revista CitriFrut, Vol. 28, No. 2, Julio-Diciembre.

Mutombo, F. I. and Glen, B. 2016. Performance analysis of thermosyphon hybrid photovoltaic thermal collector. Engineering, University of KwaZulu-Natal, South Africa. Journal of Energy in Southern Africa. Vol. 27 No 1.

Nixon, J.; Kumar, P.; Davies, P. 2013. An interdisciplinary approach to designing and evaluating a hybrid solar-biomass power plant. School of Engineering and Applied Science, Aston University, Birmingham, UK. International Journal of Energy Sector Management Vol. 7 No. 3, 2013 pp. 321-337 q Emerald Group Publishing Limited 1750-6220 DOI 10.1108/IJESM-04-2013-0002.

Orozco, H. C. and Bedoya, L. F. 2007. Calculo del flujo másico y caudal de aire para un ventilador utilizado en silos para secado para del café [Fan mass air flow rate for drying coffee]. Scientia et Technica Año XIII, No 35, Agosto. Universidad Tecnológica de Pereira. ISSN 0122-1701.

QueirozI, A.; Hermeval J. DantasII; Rossana M. F. de FigueirêdoI; Karla dos S. Melo.2011. Solar drying of jackfruit almonds. Secagem solar de amêndoas de jaca. Engenharia Agrícola. POST-HARVEST SCIENCE AND TECHNOLOGY. Print version ISSN 0100-6916, Eng. Agríc. vol.31 no.6 Jaboticabal Dec. 2011.

Quintanar, O. J. and Roa, D. R. 2017. Thermal and financial evaluation of the drying process of coffee bean in an active solar dryer type greenhouse. Revista Mexicana de Ciencias Agrícolas Vol.8 Núm.2 15 de Febrero - 31 de Marzo, 2017 p. 321-331.

Salas, G. C.; Moya, R. M.; Córdoba F. R. 2008. Diseño y construcción de un secador solar para madera. [Design and construction of a solar dryer for wood]Instituto Tecnológico de Costa Rica Escuela de Ingeniería Forestal Centro de Investigación en Integración Bosque Industria (CIIBI). Kurú: Revista Forestal (Costa Rica) 5 (14). Costa Rica.

Saravia, L.; Alía, D.; Sánchez, B. 2007. El diseño de secadores solares usando las curvas de secado del producto. [The design of solar dryers using the drying curves of the product.] Avances en Energías Renovables y Medio Ambiente Vol. 11. Impreso en la Argentina. ISSN 0329-5184. Centro de Desarrollo e Investigación en Termofluidos CEDIT.

Sivipaucar, C.; Curo, H; Eder Huancahuari, Víctor Llantoy and Andrés Valderrama 2007. Calculation and construction of a solar dryer by natural convection for drying of non-traditional medicinal plants.

Sogari, N. and A. Busso. 1998. Secadero solar: balance energético. [Solar dryer: energy balance].

Sreerag T. S. and Jithish K. S. 2016. Experimental investigations of a solar dryer with and without multiple phase change materials (PCM's). Department of Mechanical Engineering, SNG College of Engineering, Kerala, India. World Journal of Engineering. Vol. 13 Iss 3 pp. 210-217. Downloaded by Instituto Tecnologico de Costa Rica At 20:28 30 January 2017 (PT).

Taransum, B., Neeru, G., Prashant, K. T. 2015. INNOVATIVE SOLAR DRYERS FOR FRUITS, VEGETABLES, HERBS AND AYURVEDIC MEDICINES DRYING. International Journal of Engineering Research and General Science. Volume 3, Issue 5, September-October, ISSN 2091-2730 883 www.ijergs.org.

Tarigan, E.; Kalirungkut, R.; Perapong Tekasakul, P. 2007. A small-scale solar agricultural dryer with biomass burner and heat storage back-up heater. Universitas Surabaya, 60292 Indonesia Prince of Songkla University Hat Yai, Songklha 90110 Thailand. Proceedings of ISES Solar World Congress: Solar Energy and Human Settlement.

Tiwari, A. 2016. A Review on Solar Drying of Agricultural Produce. Department of Food Science and Technology, NIFTEM, Kundli, India. Journal of Food J Processing & Technology. Tiwari. J Food Process Technol 2016, 7:9 DOI: 10.4172/2157-7110.1000623. file:///D:/Usuarios/tjguzman/Downloads/a-review-on-solar-drying-of-agricultural-produce-2157-7110-1000623.pdf, recuperada 22 de marzo del 2018.

Treyball, R. E. 2016. "Operaciones con transferencia de masa" ["Operations with mass transfer"] Capítulo XII, Secada. Pág. 653. Repositorio digital de Universidad de las Américas. http://dspace.udla.edu.ec/bitstream/33000/4132/1/UDLA-EC-TIPI-2007-13%28S%29.pdf, recuperado el día 21 de marzo del 2018.

Vega, A.; Andrés A.; Fito, P. 2005. Modelado de la Cinética de Secado del Pimiento Rojo (Capsicum annuum L. cv Lamuyo).[Modeling the Drying Kinetics of Red Pepper (Capsicum annuum L. cv Lamuyo]. Información Tecnológica-Vol. 16 N°6-2005, págs.: 3-11. INDUSTRIA ALIMENTARIA. Chile.

Yunus, C. 2007. Transferencia de calor y masa. Un enfoque práctico. [Heat and mass transfer. A practical approach]. McGraw-Hill Companies, Inc. University of Nevada, Reno. ISBN-13: 978-970-10-6173-2; ISBN-10: 970-10-6173-X. México.