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Evaluation of Agricultural Solar Dryer Performance with Radiation Intensity

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Abstract

The moisture content in the production of agricultural plant products impacts the durability during storage, transportation costs and complexity of any subsequent industrialization process. Several techniques are used in the drying process. Due to the environmental and economic impact, the use of renewable energy sources such as solar energy is being prioritized. It is important to develop metrics that validate and guide improvements in this process and estimate the drying time of the input until reaching tolerable moisture levels, in different locations and times of the year for various products. This work proposes a methodology that correlates the solar radiation incident on an agricultural drying unit with the speed of moisture reduction of the items in process, based on values obtained from continuous moisture measurements.

Keywords: Solar Dryer, Agricultural purpose, relationship between moisture content and solar radiation.

1. Introduction

This work aims to present a continuous gravimetric moisture measurement system during the operation of a solar greenhouse drying, without the need for sample collection or operator intervention. It also measures the incident solar irradiance, integrating it over the drying time to obtain the accumulated irradiance. The correlation of these two quantities allowed for the estimation of the behavior of the process for a given agricultural product in different locations or times of the year. It also allows evaluating the impact of any improvements implemented in greenhouses.

2. Real-time Moisture and Irradiation Measurement

Solomon et al (2021) and El Sebaii et al (2011) presented functional details that enable solar greenhouses to dry agricultural products, such as grains, fruits, and leaves. Metidji (2016) focused on the use of solar dryers for dehydrating industrial waste from agricultural products, aiming at reuse as biofertilizers. El- Mesery et al (2021) and Kumar et al (2020) discussed different technologies of active and passive agricultural dryers and the speed of moisture reduction obtained in experiments. In these, moisture measurement was carried out in a sample manner, with manual collection and processing by a human operator.

The proposal to be presented in this article involves monitoring the moisture content of a batch in process without the need for human operator intervention.

There are three usual methods for measuring the moisture content in agricultural products. The resistive method is mainly indicated for measuring moisture in wood. Although it is occasionally used for measuring moisture in grains, it is not recommended for permanent monitoring installations without human operator intervention, as the electrodes undergo a surface oxidation process, causing measurement errors.

The capacitive method, on the other hand, does not allow installation inside a drying greenhouse, as it operates by keeping the samples in a completely closed compartment composed of measuring electrodes. The sampled quantity is not subjected to ventilation and heat exchange like the rest of the batch undergoing the drying process.

The gravimetric method, however, appears to be the most suitable. It allows monitoring the change in mass of a sample inside the greenhouse, provided that the measurement system reproduces the ventilation and heat exchange conditions.

This method requires the initial measuring the moisture in a sample (Mi%) before the batch enters the drying process.

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Equation 1 allows the continuous determination of the moisture content of the input during the drying process (Mt %). It is deduced from the relationship proposed by Inmetro Ordinance 402 of 2013. It is based on the initial moisture content measured (Mi%) with a commercial instrument, the initial weight of the sample (Wi), and the measurement of the weight of the sample mass (Wt).

$$Mt\% = 1 - (Wi.\frac{1-Mi\%}{Wt}) \quad \text{(eq. 1)}$$

The sample to be weighed must be exposed to the same conditions as the rest of the batch in process. Figure 1 shows the implemented prototype.

By continuously measuring the sample's moisture over time, it is possible to interrelate it with other environmental variables. Amonovich et al (2024) presented sizing details for various types of drying stations, paying special attention to details regarding the functional interaction with the incident solar irradiance.

The development consists of interrelating the speed of moisture reduction of a given input subjected to the drying station with time. It is based on the measurement of the solar irradiation available in the location and at a specific time of year.

For this, the following variables can be correlated:

- Total mass of the batch of agricultural products: m [kg].
- Initial relative humidity of the agricultural product: Mi% [%].
- Desired final moisture of the agricultural product: Mf% [%].
- Incident solar irradiation during the drying time: Et [W.m/m^2].
- Total horizontal area of solar collector: A [m^2].
- Total drying process time for moisture reduction from Mi% to Mf%: T [h].
- Type of agricultural product undergoing the drying process.
- Location where the drying station is installed.
- Month of the year the drying process is executed.

The figure of merit Θ (theta) is adopted to characterize the behavior of a drying station with different types of agricultural products. This defines the speed of water removed from a quantity of agricultural products. The value of Θ is defined by Equation 2.

$$\theta = \frac{(Mi\% - Mf\%).m}{A.T} \quad [kg / (m^2.h)] \quad \text{(eq. 2)}$$

It is concluded that:

- The higher the value of Θ (theta), the higher the yield of the drying station for processing a given input.
- The shorter the drying time (T) the higher Θ (theta) will be, indicating that the station has good yield.
- The smaller the horizontal area (A), the higher Θ (theta) will be, indicating that the station needs to occupy a small area to adequately dry a batch in each time. It indicates that the station has good energy efficiency.

The total number of days (D) for the batch process is obtained by dividing the process time by 24 hours.

$$D = \frac{T}{24h} \quad [\text{days}] \quad \text{(eq. 3)}$$

The horizontal solar irradiation throughout the drying period needs to be measured. This allows the definition of the daily average value of the incident irradiation Etd during the process, according to Equation 4.

$$Etd = \frac{Et}{D} \quad [W.h/m^2.days] \quad \text{(eq. 4)}$$

For a specific type of agricultural product, with the Θ (theta) e Et values experimentally determined, it is possible to estimate the total drying process time in another location, with a drying station of similar architecture. The relationship is linear. A given drying speed Θ (theta) of a product is obtained when subjected to a total daily average horizontal irradiation Etd.

3. Experimental Procedure

To practice the concepts, a solar drying greenhouse prototype was built, figure 1. It has a natural air convection system with solar heating. The proposed sensing system was implemented in it.

Fig.1: Greenhouse prototype with system to humidity measurement of agricultural products during dryer process.

The values of the variables regarding agricultural products, air temperature and humidity and relative humidity, the integral value of incident solar radiation throughout the drying time, are obtained as shown in figure 2.

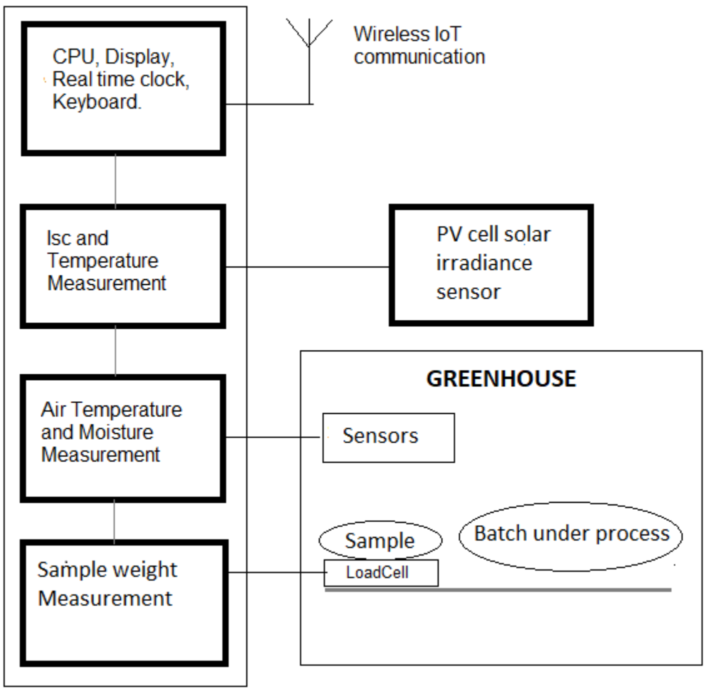

Fig. 2: Supervision and measurement system connected at Greenhouse.

3.1 Irradiance Measurement:

The irradiance was measured using the short-circuit current of a monocrystalline silicon photovoltaic cell 4 7/8" diameter, positioned horizontally on the exterior of the drying station It was previously calibrated with a Solar Power Meter SM206, yielding an Isc de 4.75 A. for 1000 W/m^2 (STC) and a thermal correction factor of +0.04%/K. The current measurement is performed by a 0.1 Ohms shunt resistor connected to an analog-to-digital converter module. The temperature sensor is a PT100 transducer fixed to the back face of the photovoltaic cell. The irradiance measurement accuracy is better than 3.5%.

The irradiance (W/m^2) is measured at a rate of one sample per second. Over a 5-minute period, the average irradiance value is calculated and converted to an irradiation value (W.h/m2). This value is transmitted to the database via the IoT system.

3.2 Sample Moisture Measurement of Agricultural Product:

The method for determining the agricultural product's moisture is gravimetric. A platform with similar characteristics to the drying station platform was constructed. The weight is measured using two strain gauge load cells with a capacity of 20 kgf. The sample is arranged on the platform at a height compatible with the rest of the batch in process, located in the drying station. The weight measurement is performed every 5 minutes. The conversion to the agricultural product's relative moisture is carried out according to Equation 1 previously presented.

Fig. 3: Gravimetric humidity measurement system in the prototype greenhouse

The moisture in a batch of cocoa measured during drying process in greenhouse, was compared with standard procedure in the laboratory. The accuracy is better than 0.50 % RH

In addition to solar radiation and moisture content, the humidity and air temperature inside the greenhouse are also monitored for later correlation.

4. Results and Discussion

The technique described was applied to a 50 kg batch of cocoa, the seed of the Theobroma Cacao fruit. Cocoa has a thick shell, thus presenting a slow drying rate. The experiments were carried out with the reduced-scale prototype station presented in Figure 1, in the city of São Leopoldo (SL) – Brazil, in May 2025. The data obtained are:

- Agricultural product: cocoa.
- Initial moisture of the agricultural product: Mi% = 52.4 %.
- Desired final moisture: Mf% = 23.5 %.
- Greenhouse horizontal area to capture solar energy: A = 1.66 m x 1,00 m = 1.66 m^2.
- Total drying process time: T= 3 dias, 23 hrs and 36 minutes ≈ 120 hrs.
- Number of days in process: D = T / 24 hrs = 5 days.
- Drying speed: ϴ cacau (SL) = $\frac{(Mi\%-Mf\%).m}{A.T} = \frac{(0.524-0.235).50\,kg}{1.66\,m2\,.\,120\,h} = 0.073$ kg / (m^2.h).

- Total irradiation measured = 9,829 W.h /m^2
- Total daily irradiation measured during the period: $Etd\ (SL) = 9{,}829$ W.h /m^2 / 5 days = 1,964 W.h/m^2.day

Estimate of the drying speed in a similar station, for the cocoa input, with the same initial moisture and the same final moisture, located near the city of Belém – Brazil in August:

- Peak sun hours per day $Etd(Belém)$: 5,250 W.h /m^2.
- ϴ cacau (Belém) = $\left(\frac{\theta\ cacau\ (SL)}{Etd(SL)}\right.\ .Etd(Belém) = \left(\frac{0.073\frac{kg}{m2}.h}{1{,}964\ W.\frac{h}{m2}.day}\right).5{,}250\ W.h/$m^2=0.193 kg/(m^2.h)

The expected process time at the drying station in Belém is reduced to approximately 46 hours that is, it is approximately three times faster than the same process in São Leopoldo, using similar greenhouse.

It is concluded that the methodology provides data that allows the estimation of the drying speed, based on historical daily irradiation data or peak sun hour per day. This parameter allows the comparison of the performance of drying stations located in different places. It also allows quantifying the productivity performance of stations in different locations and architectures, for different times of the year.

The data obtained in the executed experiments are presented in Figure 4. It is possible to observe the delay in the temperature increase response inside the greenhouse compared to the increase in instantaneous solar irradiance. This is also true for the distortion of the daily solar irradiance graph, due to the accidental shading present at the process site.

It is important to emphasize that the data obtained for a specific drying station in a specific climatic season are intimately correlated with the type of agricultural product processed.

The methodology presented is eminently comparative. It can be applied to diverse architectures of solar drying stations.

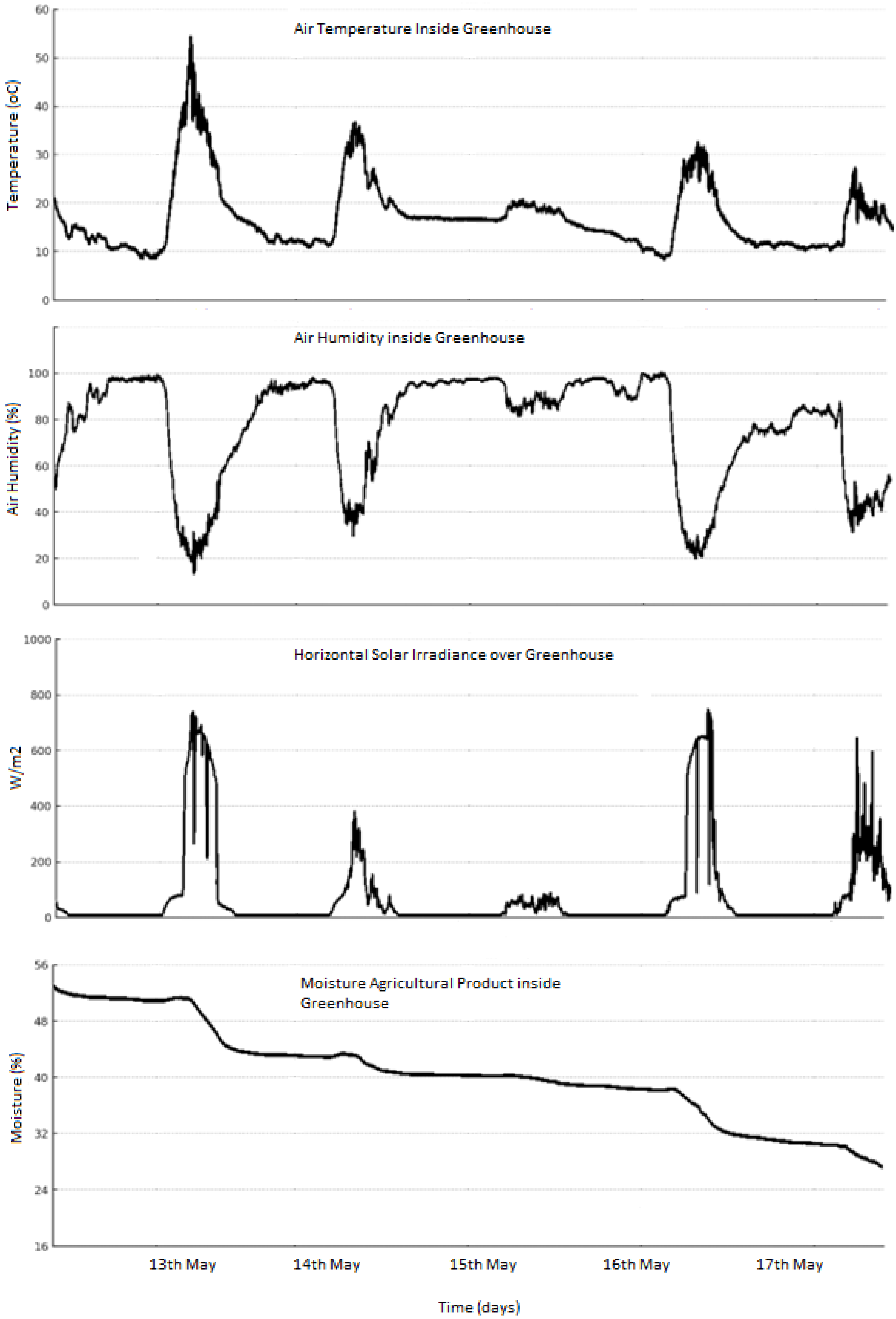

Fig 4.: Real-time relationship obtained in the experiment between the air temperature and humidity inside the greenhouse, the incident solar irradiance on the horizontal plane, and the evolution of the agricultural product's moisture during five days drying process.

5. Conclusion

The analysis of the results will allow us to evaluate the productivity of the agricultural product solar drying process, as well as the dimensioning of the infrastructure to meet demand. The metrics presented will support the check of improvements effectiveness in the process. As a continuation of this development, new tests are being executed to verify the repeatability of the measured data. Measurements are also being executed and correlated to the process speed with the external temperature of the drying station.

6. Acknowledgements

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7. References

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