DEVELOPMENT AND PERFORMANCE EVALUATION OF A HYBRID SOLAR DRYER WITH LATENT HEAT STORAGE AND DEHUMIDIFICATION SYSTEMS

ABSTRACT

Drying agricultural products has become an essential technique for preservation, but current drying methods often prove to be energy-intensive, costly, and unsuitable for the needs of local small and medium-sized enterprises (PME/PMI). In this study a hybrid solar dryer has been designed specifically to meet the needs of PME/PMI. The current limits to the development of solar drying in Africa are low efficiency and low autonomy. To remove these bottlenecks, thermal storage and air dehumidification systems are often used.

This article firstly, presents a brief review, not only of thermal storage materials but also of dehumidification systems. This review led to the choice of paraffin and silica gel respectively for thermal storage and dehumidification of drying air.

The selected materials were subsequently implemented in an indirect hybrid dryer with a drying capacity of up to 50 kg of fruits and vegetables. It is made up of an aluminum absorber painted in matt black, 1.5 mm thick. Its exterior structure is made of steel separated from the interior face made of stainless steel, by a layer of glass wool, 30 mm thick. Performance tests are carried out on the classic dryer, then with the dryer integrating silica gel on the one hand and on the other hand, the dryer with paraffin. The tests were conducted in Cotonou (latitude: 6°21'50"N; longitude: 2°26'32"E) during the month of November with an average irradiation of 137.23 kWh/m² received on the horizontal plane with an average temperature of 27.4°C.The experiments are carried out over several days so as to be able to extract, for each of the improved dryers, 03 days similar, from the point of view of daily irradiation, to the tests on conventional dryers. Tests carried out on the dryer with the new latent heat storage system reveal an increase in efficiency of 3% compared to the classic dryer. The proposed dehumidification solution showed a good dehumidification rate of 16% which helps to improve the overall efficiency of the dryer.In practice, this improvement in performance will result in a reduction in drying time and energy consumption.These first promising experimental results will be validated with other tests which will be carried out over several consecutive days, also varying the quantities of paraffin and silica gel.

Keywords:solar dryer, Latent thermal storage, dehumidification.

Introduction

Post-harvest lossesof fruits and vegetables, recorded each year in sub-Saharan African countries are enormous. About 1/3 of food production is lost or wasted each year, emitting the equivalent amount of CO_2 as 1.5 million cars [1]For example, in Benin, post-harvest losses for the pineapple sector are estimated at around 70% throughout the value chain [2] However, in Benin, according to the National Institute of Statistics and Economic Analysis (INSAE), in August 2017, 42.9% of the population was estimated to be food insecure, including 9.6% (i.e. 80,000 people) who were food insecure. To prevent the deterioration of perishable products such as fruit and vegetables, several preservation techniques exist, including drying. Drying agricultural products has become an essential technique, but current drying methods are often energy-intensive, expensive, and unsuitable for the needs of local small and medium-sized enterprises (SMEs).

Our team previously designed [3] a hybrid and connected solar dryer, specially to meet the needs of SMEs. The dryer is intended for drying fruits and vegetables: such as pineapple, mango, banana, spirulina etc. It operates through the hybridization of four energy sources, namely solar thermal, solar photovoltaic, gas and conventional electricity (public grid). The dryer currently has low efficienciesand is very affected by fluctuations in solar radiation. To optimize its efficiency and increase its autonomy, we aim to equip it with an improved thermal storage system and an air dehumidification system.

Firstly, a state of the art is carried out not only on existing storage systems but also on-air dehumidification systems generally used in drying. Material choices were then made for thermal storage and dehumidification. The initial tests and results are subsequently presentedon the dryer after adding storage and a dehumidification bed.

1 STATE OF THE ART

1.1 BRIEF REVIEW ON THERMAL STORAGE

To overcome the problem of intermittent solar energy, it is possible to use thermal storage to extend drying at a constant temperature. Thermal storage works by cycle in which we can observe three phases: charging, storage, discharge [4]. There are three modes of thermal storage, namely:

- Sensitive storage
- Latent storage
- Thermochemical storage

K. Kant et al.,[5] have made a classification of the several types of thermal storage presented below:

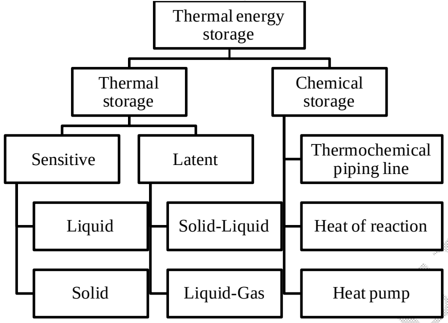


Figure 1 :Classification of the different types of thermal energy storage.

i. Sensible heat storage materials

A list of sensitive heat storage materials has been identified. The table below presents those available in Africa sub-Saharan context [6].

Table 1 : Africa sub-Saharan available sensible heat storage materials

Storage Materials	Thermal conductivity (W.m^{-1}. K^{-1})	Density (kg/m^3)	Heat capacity by weight (kJ.kg-1. K-1)
Roche Granite	1.47	1468.11	0.627
Concrete	1.5	2200	0.85
Sand	1.21	1605.08	0.546
Water	0.58	1000(liquid)	4.184
Laterite	1.07	1093.44	0.499
Laterite rock	1.17	1142.13	0.559
Clay	**2.16**	**1187.70**	**1.398**

ii. Latent Heat Storage Materials

Reddy et al., [7]classified storage materials by latent heat.

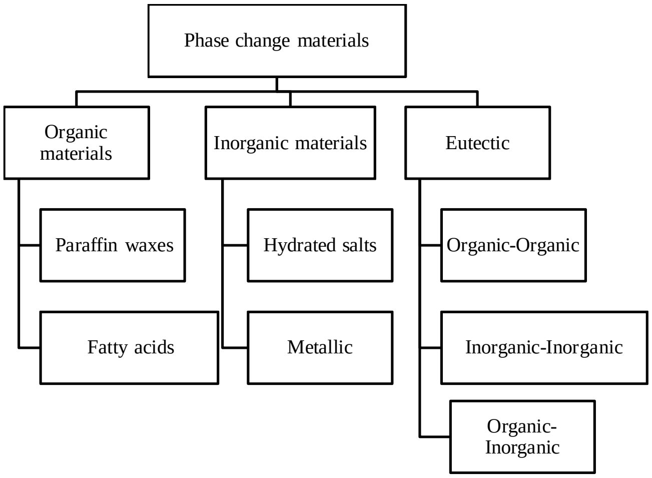


Figure 2 : Classification of Phase Change Materials

The following table compares organic and inorganic PCMs:

Table 2: Main characteristics of organic and inorganic PCMs

Properties	**Organic**		**Inorganic**	
	Paraffin wax	**Fatty acids**	**Salt Hydrates**	**Metals**
Corrosion resistant	Non applicable	Non applicable	Non applicable	No resistant
Cost	Low	Medium	High	High
Latent Phase Change Heat (J/g)	Medium (200 – 220)	Medium (146-218)	High (184-264)	High
Thermal Conductivity (W/m. K)	Low (0.17-0.35)	Medium (0.15-1.6)	High (0.46-5)	High (8.3 - 29.3)

After analyzing this table, we chose paraffin wax because of its availability, low cost compared to other materials. The paraffin has also the highest latent phase change heatand an acceptable conductivity.Also,Paraffin has remarkable long-term thermal and chemical stability, retaining its properties after thousands of melting and solidification cycles [8]. Paraffins based thermal energy storage system have shown they effectiveness for small-scale thermal energy storage especially for air conditioning in the built environment [9], [10]. This explain why, paraffin wax is the most widely used PCM [11],[12] especially in solar dryers ([13],[14],[15]). A study [16] show that the paraffin based thermal storage system efficiency decreases 12.7% after 10,000 fast charging cycles (10°C/min). The use of fatty acids is not widespread, as it costs more than paraffin and is flammable[11].

iii. Thermal storage system

In this section, we present some of the thermal storage systems identified.

A study [17]experimented with a solar dryer incorporating heat-sensitive thermal storage using sand and aluminum scrap as thermal storage materials. They observe not only an increased drying time by about 4 hours per day after sunset but also, a drying of chili pepper from 72.8% to approximately 9.2% and 9.7% in the bottom and top trays respectively. The thermal efficiency of the solar dryer has been estimated to be around 21%.

SY Khaldi[18] did a study on a solar dryer incorporating a gravel thermal bed. For a thermal bed thickness of 0.05m, a maximum temperature of 50.35°C is obtained in the drying chamber and for a thermal bed thickness of 0.15m, a maximum temperature of 45.85°C is obtained in the drying chamber for an efficiency of 44.59%. The drying time is estimated at 21 hours. A higher thickness promotes storage and decreases the maximum temperature.

WB Chaouch et al. [19] worked on a natural convection solar dryer with thermal storage in which rock pebbles were used as material.

In this case, the storage of sensible heat by the pebble bed improved the daytime thermal efficiency of the direct drying chamber by 11.8% compared to use without storage. 28% improvement in solar collector efficiency[19].

A solar dryer integrating a latent heat storage system was evaluated by[20]. Paraffin wax was used as a thermal storage material.The moisture content of the dried sample in the dryer increased from the initial moisture content of 83.4% to the final moisture content of 6.7% in 45 h, while the sun-dried sample took 80 h[20].

A study [21] experimented with a solar greenhouse integrating a latent heat storage system with paraffin wax as a thermal storage material. The experimental results show that the air temperature inside the solar greenhouse with PCM is higher than that of other dryers by about 7.5°C during the entire night period. The relative humidity in the drying chamber with PCM, is reduced by 95% in 30 hours in the dryer with PCM, whereas it took 55 hours in the dryer without PCM and 75 hours in full sun.

An experiment on forced convection solar air heaters using a finned absorber plate lined with latent heat storage materials (paraffin wax) and another flat absorber plate, both absorbers are painted black[22].
The results showed that the outlet temperature increased by 5°C and the heat storage time was increased up to 3 h by increasing the energy efficiency was from 2 to 15%.

1.2 BRIEF REVIEW ON AIR DEHUMIDIFICATION SYSTEMS

In dehumidification-assisted drying, the driving force of moisture mass transfer can be enhanced by lowering the relative humidity of the drying medium, resulting in a more efficient drying system. A study [23]indicate that five (05) types of air dehumidification systems are developed and applied nowadays:

- Condensation dehumidification
- Dehumidification by heating
- Membrane dehumidification
- Absorption dehumidification
- Adsorption dehumidification

They [23] reviewed the strengths and weaknesses of different air dehumidification methods. It shows that air dehumidification using a solid adsorbent is more interesting in terms of operability, efficiency, investment, and maintenance.
The following table shows the properties of three (03) solid adsorbents at room temperature of 27°C:

Table 3: Properties of some solid adsorbents at 27°C [23]

Adsorbents solids	Relative humidity of the medium (%)	Adsorption capacity (g water/gadsorbent)	Regeneration Temperature (°C)
Silica gel	60	0.08 – 0.36	80 - 150
	7	0.02 – 0.05	
Zeolites	60	0.02-0.30	250-350
	7	0-0.25	
Activated carbon	60	0.18-0.29	70
	7	0-0.4	

Silica gel is thewell-known and widely used sorption material for dehumidification in direct and indirect forced convection solar dryers[24].Silica gel is particularly effective for solar drying applications compared to other solid adsorbents like activated alumina and activated charcoal, as it demonstrates higher adsorption rates and retains moisture for longer periods, making it ideal for low-temperature solar regeneration systems [25].In a study [26] comparing the performance of three adsorbents (silica gel, zeolite 13X and zeolite 4A) in an adsorption thermal energy storage system, zeolite 13X offers the best storage density per unit mass, while silica gel excels in storage density per unit volume and reaction time, thanks to its high thermal conductivity and superior water adsorption capacity, making it more effective for solar drying applications. Some solar dryers with dehumidification systems are shown below:
A dehumidification system working with the desiccant wheel is shown below:

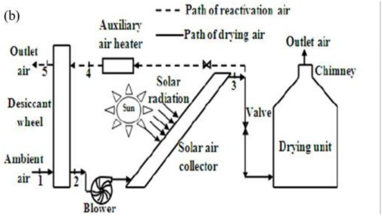


Figure 3 : Dehumidification system with desiccant wheel.

Thanks to the desiccant wheel, the air temperature increased from 65°C to 82°C and the air humidity level increased from 15g of water/kg to 8.8g of water/kg[27].

2 MATERIALS AND METHODS

The solar dryer used for the tests is an indirect hybrid dryer with a drying capacity of up to 50 kg of fruits and vegetables. It is made up of an aluminum absorber painted in matt black, 1.5 mm thick. Its exterior structure is made of steel separated from the interior face made of stainless steel, by a layer of glass wool, 30 mm thick. Roughly, the solar dryer is made up of four (04) main parts:

i. **The solar collector:** It is in this unit that the air receives the solar thermal energy necessary to dry the product. It consists of (1) an "**absorber**" made of aluminum to which we have added a "matte black" coating to reinforce the absorption coefficient; (2) glass wool "**insulation**" to limit heat loss and (3) a transparent "glass" cover.

ii. **The drying chamber:** It is inside this unit that the products are dried. It consists of an inner stainless-steel carcass and an outer steel carcass; the two carcasses are separated by glass wool insulation to limit losses; There are also three (03) stainless steel racks and a chimney for the evacuation of air from the interior.

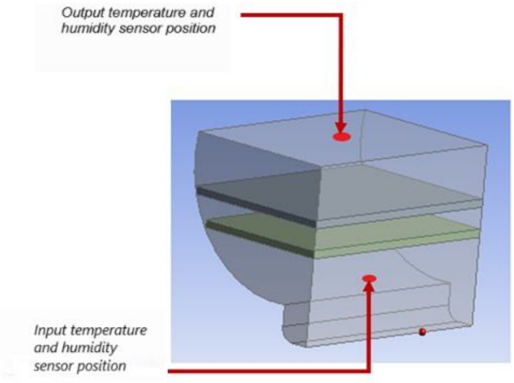
iii. **The funnel:** This is a duct that connects the sensor to the drying chamber. It is made of steel and insulated from the outside environment by glass wool.

Table 3 shows the materials and dimensions of the dryer.

Table4 : Dimensions and materials of manufacture of the dryer

Component	**Hardware**	**Size (mm) (L*W*h)**	**Material properties**		
			Thermal conductivity (W.m-1. K-1)	**Density (kg.m-3)**	**Specific heat ($^{J.kg-1}$. K-1)**
Absorber	Aluminum	1 500 * 740 *1,5	237	2700	897
Sensor casing	Steel	1 500 * 740 * 150 Thickness 1.5	80,2	7870	447
Fins (air opening)		Thickness 1.5 Diameter 50	80,2	7870	447
Carcass drying chamber		800 * 800 * 600 Thickness 30	80,2	7870	447
Glass lid	Glass	1 500 * 740 Thickness 4	1,05	2500	670
Side Insulation	Glass wool	Thickness 30	0,037	25	1030
Bottom insulation		Thickness 30	0,037	25	1030

Figure 4.a shows the dryer with the paraffin introduced into cylindrical profiles, welded to the absorber Figure 4.b shows, at the top, the bed of silica gel installed at the level of the funnel, on the drying air flow. Below the silica gel bed, it is presented the positioning of the sensors for measuring temperature and humidity before and after the silica gel bed.



(a) (b)

Figure 4: The solar dryer with the positioning of paraffin and silica gel bed

Experimental tests were conducted to verify the performance of the solar dryer with thermal storage. These are the following tests: i. Solar Mode Test (Without Thermal Storage), ii. Solar test (with thermal storage). Experimental data were recorded from 8:00 a.m. in the morning to 6:00 p.m. in the evening.

To conduct the measurements of the various parameters, we used the equipment presented in the following table:

Table 5 : Measuring devices.

Measuring devices	**Characteristics**
Uni-T UT330A Data Logger	Range: 80°C; Accuracy: 0.5°C
Anemometer PM6252B	Range: 30m/s; 60°C; 100% RH
TES 1333 Solarimeter	Range: 2000W/m²; Accuracy: 0.1 W/m². Spectral sensitivity: 400~1100nm

The efficiency of the solar collector (is defined as the ratio between the heat received by the drying air and the irradiation incident on the collector in each time interval. It is calculated from equation 1:η_c)

$$\eta_{CS} = \frac{1}{36} \times \sum_{t=1}^{36} \frac{\dot{m}_t C_p (T_{out\_t} - T_{in\_t})}{I_t S} \qquad (1)$$

$$\dot{m}_t = \rho S_2 v_t$$

$\dot{m}_t$	Air Mass Flow Rate (kg/s)
C_p	Heat capacity of air (J/K.kg)
T_{out_t}	Solar collector outlet air temperature (°C)
T_{in_t}	Air temperature at the inlet of the solar collector (°C)
I_t	Solar Irradiance (W/m²)
S	Solar collector area (m²)
ρ	Air density (kg/m3)
S_2	Air opening section at solar collector outlet (m²)
v_t	Air velocity at the solar collector outlet (m/s)

3 RESULTS AND DISCUSSIONS

3.1 EXPERIMENTATION AND CHARACTERIZATION OF THE DRYER WITH LATENT STORAGE

The tests were conducted in Cotonou (latitude: 6°21'50"N; longitude: 2°26'32"E) during the month of November with an average irradiation of 137.23 kWh/m² received on the horizontal plane with an average temperature of 27.4°C.

The following figure shows the variation of solar irradiation over one year on the site:

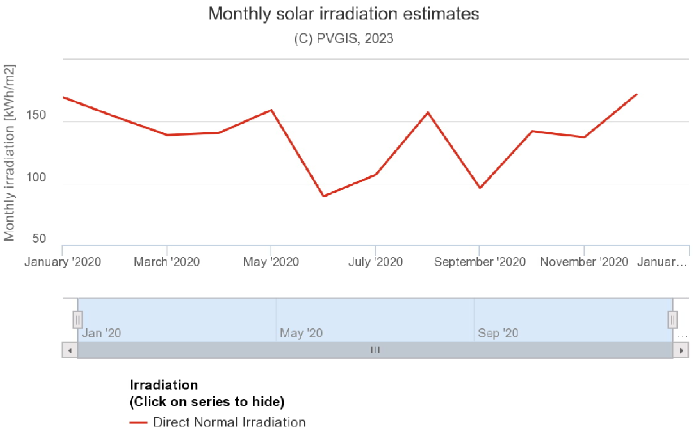
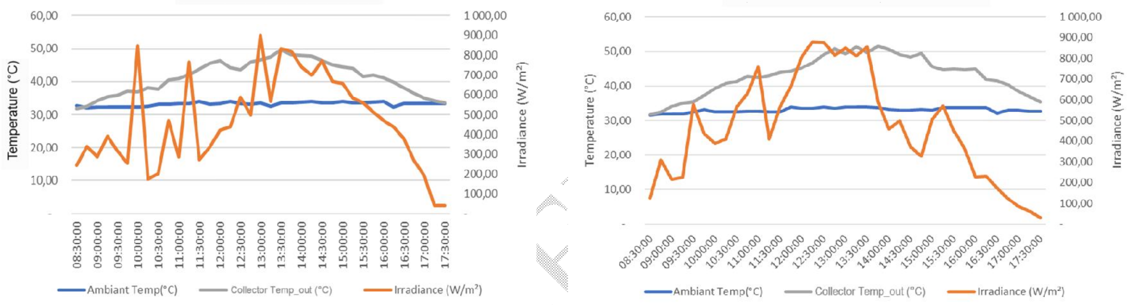


Figure 5:Variation in irradiation at the drying site (PVGIS, 2023)

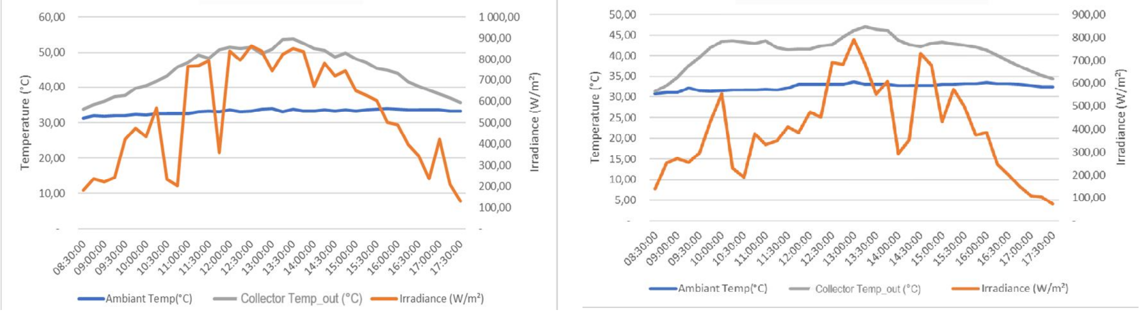
The figures below show on the right the tests carried out with the dryer without paraffin and on the right the equivalent tests (near daily irradiation) with the dryer containing paraffin.



(a) Paraffin-free solar dryer

(b) Solar dryer with paraffin

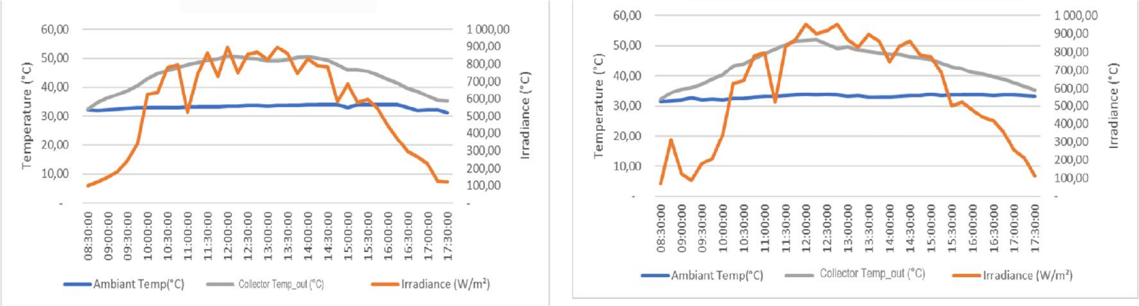
Figure 6: Variation of the temperature at the outlet of the solar collector, the ambient environment, and the solar irradiance test n°1.



(a) Paraffin-free solar dryer

(b) Solar dryer with paraffin

Figure 7:Variation of the temperature at the outlet of the solar collector, the ambient environment, and the solar irradiance test n°2.



(a) Paraffin-free solar dryer

(b) Solar dryer with paraffin

Figure 8 :Variation of the temperature at the outlet of the solar collector, the ambient environment, and the solar irradiance test n°3.

The table below shows the calculated dryer efficiencies for each of the six tests.

Table 6 : Test results and performance indicators

Types de tests	**Paraffin wax quantity (kg)**	**Average daily irradiation(Wh)**	**Solar Collector Efficiency %**
Solar Collector + Thermal Storage Tests	1,74	4226.40	28.79
		3577.73	28.23
		5303.74	22.27
Solar Collector Test	-	4228.09	21.25
		4907.30	26.77
		5122.49	23.81

These tests reveal efficiencies of 23.94 and 26.43% respectively for the solar mode and the solar + thermal storage mode.

From the analysis of the curves and the table, it appears that the addition of paraffin does not cause a significant variation in the temperature of the dryer at the end of the day. However, we note a positive effect of latent storage on efficiency which shows a slight increase of 3%. This reflects a greater quantity of energy absorbed due to the presence of storage.

3.2 AIR DEHUMIDIFICATION USING SILICA GEL.

Several tests were carried out on the dryer with or without silica gel in order to assess the effectiveness of the dehumidification of the air at the entrance to the drying chamber. The figure below shows the results of one of these tests. It shows the change in relative humidity before and after silica gel.

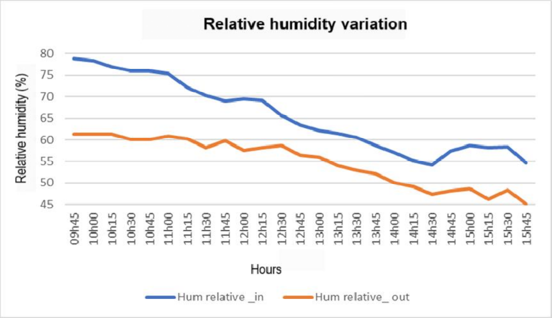


Figure 9: Variation in relative humidity before and after silica gel.

Several tests were carried out on the dryer with or without silica gel in order to assess the effectiveness of the dehumidification of the air at the entrance to the drying chamber. The previous figure shows the results of one of these tests. Overall, the addition of silica gel made it possible to reduce the humidity of the drying air by around 16%. This will undoubtedly result in a reduction in drying time and a concomitant increase in efficiency. These first experimental results will be validated with other tests which will be carried out over several consecutive days, also varying the quantities of paraffin and silica gel.

CONCLUSION

This paper presented the results obtained from the implementation of the new latent heat storage system in the solar collector. These results reveal a 3% better efficiency of the sensor thanks to thermal storage. This improvement in efficiency can result in concrete benefits for solar drying, such as a reduction in drying time or an increase in drying capacity. To go further, it would be relevant to evaluate the impact of this latent storage on the overall performance of the solar dryer. This evaluation should consider the efficiency of the complete drying system and the final quality of the dried products.

The proposed dehumidification solution is simple to install and use. The test conducted with this dehumidification device showed a dehumidification rate of 16%. For the next steps, we recommend additional dehumidification tests to achieve an average dehumidification rate as well as drying tests to evaluate the effect of dehumidification on the drying of the products.

In summary, this study demonstrates the potential of latent heat thermal storage to improve the efficiency of solar dryers. The silica gel dehumidification solution is also interesting for optimizing drying. These technologies combined pave the way for more efficient and environmentally friendly solar drying.

Disclaimer (Artificial intelligence)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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