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Smart Mini Solar Dryer for Laboratory Pilot

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***Abstract*— This research was prompted by the alarming prevalence of malnutrition among children in Madagascar, exacerbated by the impact of COVID-19. The current state of knowledge on the solar drying of algae, particularly spirulina, which could significantly contribute to addressing this pressing issue, is not well-established. Consequently, ongoing laboratory investigations necessitate appropriate apparatus. This article introduces the design of a device tailored for experimental studies, with the goal of enhancing the functionality of an intelligent solar dryer. A crucial aspect involves creating a cost-effective experimental configuration suitable for adoption by African research laboratories, often constrained by limited resources. The developed device, incorporating smart sensors, comprises a solid adsorption dehumidifier, an embedded computer system with regulation, a photovoltaic system with storage, and inclusive user interfaces. The primary objective was to optimize food dehydration by initially dehumidifying the air. The results obtained demonstrate that the device facilitates faster drying with optimal temperature regulation. The process monitoring is facilitated by a mobile application. In terms of future research, the focus will shift towards achieving optimal low-temperature drying of spirulina. Regarding education, the setup will be employed to implement interdisciplinary practical exercises encompassing thermal, computer, electronic, and energy-related aspects.**

***Keywords*— smart solar dryer, malnutrition, Madagascar, inclusive user interface, solid adsorption dehumidifier, solar energy, regulation, energy optimization, interdisciplinary pratical work**

I. INTRODUCTION

Drying food using solar techniques is a widely adopted method for food preservation. This approach is especially relevant for African countries, where drying enables storage and utilization of surplus produce, facilitating market availability during scarcity periods. The seasonal harvesting challenge of highly perishable fruits and vegetables makes dried product sales a lucrative income source for rural families. This study was motivated by observed food insecurity in Madagascar, where 33% of the population faces food insecurity, according to the World Bank [1]. Despite agricultural challenges leading to perishability, the sector contributes significantly to Madagascar's GDP and employs 80% of the active population [2]. Food drying not only promises increased yields but also provides an alternative means to access food. Indirect solar drying has demonstrated superiority over direct drying methods [3]. Maundu et al.'s work presents a natural convection and updraft indirect solar dryer supporting this concept [4], and Simate's study in Zambia showed the efficiency of indirect dryers over mixed solar dryers [5]. Indirect solar drying, acknowledged for better control and superior product quality, has gained widespread recognition [6].

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To enhance the performance of indirect solar dryers, various authors have integrated smart sensors to manage drying parameters. In Indonesia, N. Hananda et al. [7] implemented an intelligent solar dryer, well-received by local coffee farmers, as a superior method for coffee drying compared to traditional sun-drying. B.A. Anand and his team found that smart dryers with microcontroller-based controllers are the most effective, allowing controlled variations in drying chamber temperature and humidity [8]. Experimental results by B. Krishna Kumarn et al. showcased the superior performance of an intelligent solar tunnel dryer, enabling faster drying of agricultural products [9].
While cited studies are valuable for drying a majority of foods, more sophisticated devices are required for certain plants or algae like spirulina to control drying parameters further. Therefore, laboratory studies remain essential, demanding tailored devices. Notably, a solar dryer typically consists of different modules, individually optimized based on the product and usage environment. This article proposes a device facilitating such an approach, aiming to create an inexpensive experimental setup for African research laboratories often constrained by limited resources. The proposed device includes a specific air dehumidification module before food dehydration through thermal transfer. Then, a very cost-effective simple regulation module, an autonomous photovoltaic energy production system with battery storage, and an inclusive human-machine interface are used.
The second section of the article details the design and implementation of various modules, with performance tests presented in Section 3. The final section discusses the results and outlines potential applications for this experimental setup.

II. . MATERIALS AND METHODS

A. Block Diagram Description of the Device

The system functions on a global scale by utilizing solar energy to dry products. Initially, a dehumidifier decreases the moisture in the incoming air. Then, a solar collector with double glazing warms up this air, contributing to its temperature increase. The heated air is then directed into a drying chamber with meshed shelves holding the products to be dried. Throughout this process, a built-in electronic module monitors and regulates the temperature, sending real-time data online. To power the electronic control module, electrical energy comes from a photovoltaic panel connected to a battery. Finally, a mobile application acts as the user interface for controlling the device and remotely visualizing data. The entire system enables efficient and eco-friendly drying through the use of solar energy and precise temperature control.

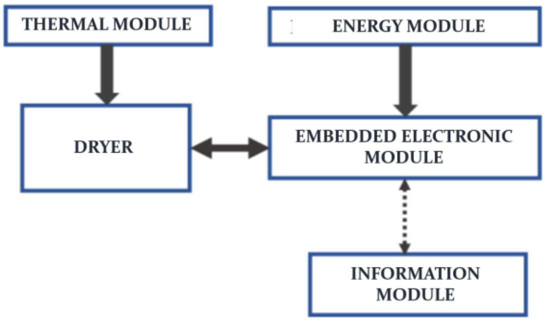

Fig. 1. Descriptive block diagram of the device

B. Multi-Sensor Instrumental System Controlled by ESP32

Smart dehydration is a regulated process overseen by a fan, ensuring the drying chamber maintains a specific temperature between 35°C and 82°C to achieve the desired moisture content for product preservation. In the case of bananas, the optimal drying temperature is set at 60°C. While the typical drying time for a food item is usually determined empirically, this approach has limitations due to variations in food characteristics. In response, we have incorporated an intelligent system that measures the air's humidity at the oven's output. The drying process for bananas halts when the relative humidity in the chamber reaches 20%.
This device is structured into four components, as outlined in our system's block diagram:

- Data Capture Block: Captures physical quantities at various locations.
- Data Processing Block: Processes the captured data through a processing unit.
- Regulation Block: Regulates the intelligent dehydration process.
- User Interface Block: Enables users to visualize the drying process and interact with the system on-site.

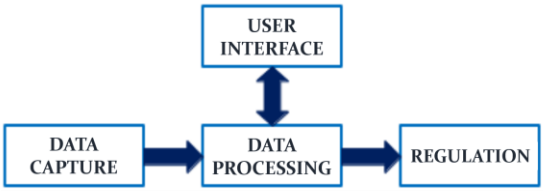

Fig. 2. Block Diagram of the Electronic Device

In the setup, electronic components such as DHT11, DHT22, and BME280 sensors are essential for capturing data like temperature, relative humidity, and pressure at various locations. The data is processed by an ESP32 microcontroller, and a fan is incorporated for regulation. Additionally, a screen and keyboard are integrated to facilitate user interaction with the device on-site.
For regulation, a bang-bang controller has been employed, given that temperature undergoes relatively slow dynamic variations. In our dryer's scenario, the drying process occurs gradually with solar input, without external electrical energy. The challenge arises when the dryer's temperature exceeds the desired drying temperature. In such cases, the fan is activated to expel hot air outside the dryer. The block diagram illustrating this regulation is as follows:

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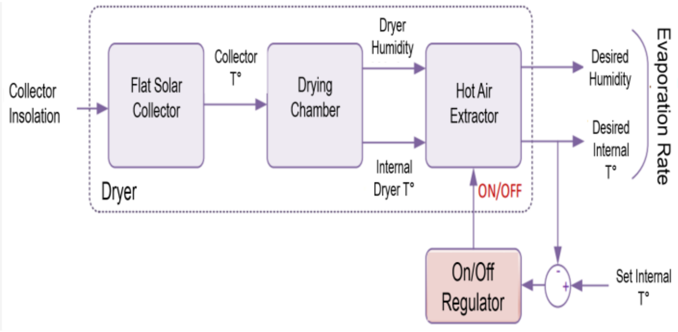

Fig. 3. Closed-Loop System Block Diagram in Case of Discontinuous Regulation Action

For the implementation of the bang-bang controller, as soon as the dryer's temperature exceeds the setpoint value, the controller detects it and activates the fan. However, a slight temperature variation around the setpoint will trigger the fan's start or stop.

This is impractical since a significant current is required for each start of a motor at rest, potentially causing damage. Thus, a temperature variation range of 2°C is defined for fan activation, as illustrated in Figure 4. This differential is represented by the upward arrow, indicating fan activation, and the downward arrow, indicating fan deactivation.

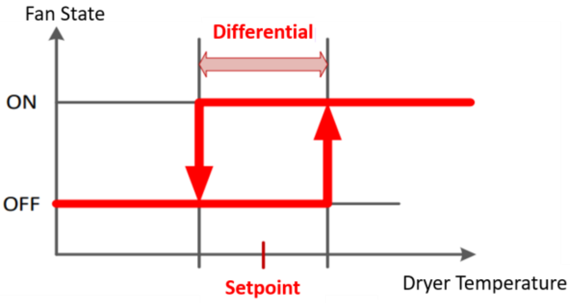

Fig. 4. Operating Diagram of the Bang-Bang Controller

As a result, the actuator will work under better conditions if the differential is higher. However, this will cause temperature oscillation in the dryer. Therefore, a compromise between the temperature variation range and the fan's activation and deactivation must be considered. This type of controller is referred to as a hysteresis controller.

C. Development of Interfaces for the Overall Operation of a Dryer

For communication, the ESP32 microcontroller was used, capable of connecting to Wi-Fi and an online database where the data is stored. The application was designed for Android, given that 80.8% of the global population uses this operating system according to mobile statistics [10]. Moreover, the interfaces are inclusive, using images and pictograms to make usage intuitive. The application also features voice assistance and sound beeps to enhance the user experience. Here is an organizational chart describing the drying process via our mobile application:

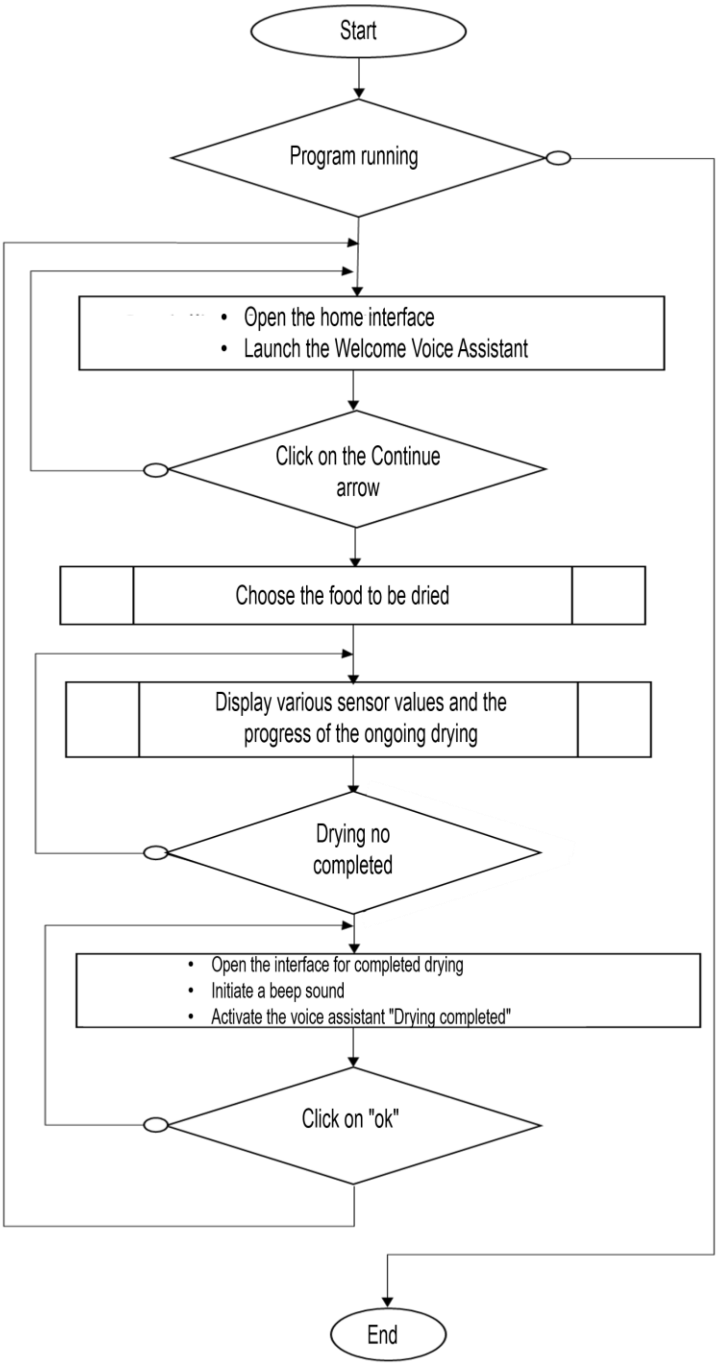

Fig. 5. Flowchart of the Drying Process

An application has been developed to serve as a user interface to:

- Control the fan by activating/deactivating the automated regulation.
- Set the drying parameters based on the type of food to be dried.
- Display various values captured by different sensors and the ongoing drying process progress.
- View data from previous drying sessions in graphical form.
- Notify the user at the end of the drying process.

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D. Study of Passive Air Dehumidification for a Food Dryer

Passive air dehumidification in a food dryer relies on an adsorption process where an adsorbent material, in our case, silica gel or zeolite, is used to extract moisture from the air.
Humid air enters the dehumidifier through natural convection and comes into contact with the adsorbent material. During this contact, the adsorbent material absorbs moisture from the air, thus reducing its water content. The now drier air is directed to the solar collector to be heated. This process repeats continuously as long as humid air enters the dehumidifier. When the silica gel is saturated, the hot air passes through the bed, releasing moisture, contrary to the adsorption process, called desorption. In this case, it would be necessary to regenerate the silica gels, which can then be reused later.
An experimental setup was constructed to study the dynamic characteristics of the adsorption dehumidification processes in a solid desiccant dehumidifier (silica gel), as illustrated in the following figure.

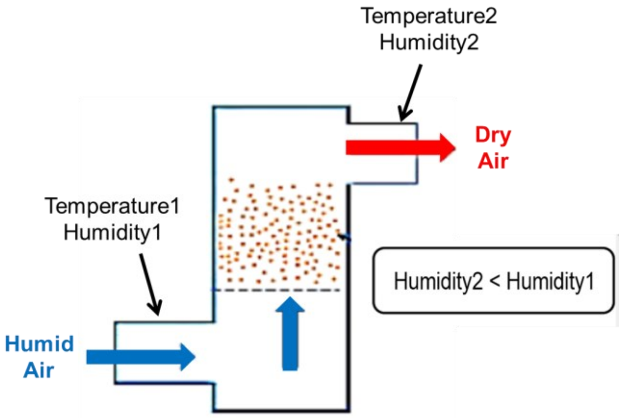

Fig. 6. Adsorption Process of the Solid Desiccant Dehumidifier

In sizing the dehumidifier, it is crucial to determine the mass of the silica gel m_{ads}. To achieve this, we first determine the mass of the adsorbate m_e, which will be considered as the adsorbed mass since it represents the quantity of water vapor in the air to be removed.
To quantify the water vapor in the air n_e, we evaluate the saturated vapor pressure ***Pvs***, which is the pressure at which the gaseous phase of a substance is in equilibrium with its liquid or solid phase at a given temperature in a closed system.

$$Pvs = \frac{Pv}{HR}[kPa] \quad (1)$$

Pv: Vapor pressure (kPa)
HR : Relative humidity (%) at **78.1%**

In an ideal solution, under constant temperature, the partial pressure of a component in the vapor phase is directly proportional to its mole fraction (Xe) in the liquid phase, as described by Raoult's Law.

$$X_e = \frac{P_{pv}}{P_{atm}} \quad (2)$$

P_{pv} : Vapor pressure (kPa)
P_{atm} : Atmospheric pressure (kPa) at **1.013 * 10 ⁵**

After sizing the solar dryer, we obtain the air flow rate inside the dryer. From this value, we determine the quantity of gas in the air. By assimilating the atmosphere to a mixture of ideal gases, we can use the ideal gas laws to calculate the quantity of water vapor in the air n_e based on air flow rate, volume, temperature, and atmospheric pressure.

$$n = \frac{P_{atm} \times V}{R.T}[mol] \quad (3)$$

V: Volume of air (m³)
T: Temperature (°C) at **25°C**
R: 8314.4 J/kmol.K
P_{atm} *:* Atmospheric pressure at **1.013 * 10 ⁵**

Thus, the quantity of water vapor in the air n_e is obtained:

$$n_e = X_e \times n[mol] \quad (4)$$

From this, we find the adsorbed mass m_e :

$$m_e = n_e \times M_{water} \quad (5)$$

- n_e : the amount of water vapor in the air
- M_{water} : Molar mass of water **18 g/mol**

Finally, based on the study of [10], we find the adsorbent mass :

$$x = \frac{adsorbed\ mass}{adsorbent\ mass} = w_0 \rho_l(T) exp\left[-D\left(T.ln\frac{P_S(T)}{P}\right)^n\right] \quad (6)$$

x : Adsorbed fraction, indicating the percentage of the maximum adsorption capacity utilized.
w_0, *D*, and *n* are distinctive parameters that define the adsorbate/adsorbent pair (water/silica gel)
ρ_l *(T):* This signifies the liquid adsorbate density at temperature
P_s and *P* represent the saturated pressure and the pressure of the adsorbate, respectively.

E. Energy System

Ensuring an uninterrupted and non-carbonated energy source necessitates the use of a photovoltaic (PV) system, which directly harnesses energy from solar irradiance. This system is complemented by a battery for effective energy storage.
In order to ascertain the appropriate specifications for the installation of the PV (photovoltaic panel), a comprehensive understanding of the loads requiring power was imperative.

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1) Sizing of the Photovoltaic Panel

TABLE I. DAILY REQUIREMENTS

Devices	Quantity	Unit Power [W]	Total Power [W]	Usage Hours	Daily Requirement [W]
Sensors	5	0.01	0.05	24	1.2
Fan	1	3.6	3.6	9	32.4
ESP32	1	1.6	1.6	24	38.4
LCD Screen	1	0.4	0.4	9	3.6
Total			5.65		75.04

$$P_C = \frac{B_j}{N_e} \quad (7)$$

P_C : Peak power of the PV system in [W_{peak}]
B_j : Daily requirement in [Wh]
N_e : Number of sunlight hours per day [h]

2) *Sizing of the Battery*

$$C = \frac{B_j \times n_j}{U_b \times 0.7} \quad (8)$$

C: Battery capacity in [Ah]
B_j : Daily requirement in [Wh]
n_j : Number of days of autonomy [d]
U_b : Battery voltage [V]

3) *Sizing of the Charge Controller*

$$I_{reg} = \frac{P_c}{U_b} \times 1.5 \quad (9)$$

- I_{reg} : Charge controller current [A]
- P_C : Peak power of the PV system [W_{peak}]
- U_b : Battery voltage [V]

III. RESULTS AND DISCUSSIONS

A. Results of the Dehumidifier Study

In determining the adsorbent mass, essential aspects such as saturated vapor pressure, ideal gas laws, and relationships specific to the adsorbate/adsorbent pair were considered to establish equations for calculating the required adsorbent mass. The following table summarizes these results:

TABLE II. RESULTS OF THE DEHUMIDIFIER SIZING

Designations	Symbols	Values
Saturated vapor pressure	*Pvs*	3,264[kPa]
Molar fraction of water vapor	X_e	0,251
Air volume	V_a	234,334[m^3]
Total amount of gas in the humid air volume	*n*	9561,997[mol]
Amount of water vapor present in the air volume	n_e	2400,061[mol]
Mass of water vapor in the air	m_e	43201,105[g]
Mass of adsorbent	*mads*	1621,110[g]

The experiment was conducted at the Applied Thermal Laboratory of Higher Polytechnic School of Antsiranana. Key experimental parameters recorded encompassed the temperature and relative humidity changes of the air, which were captured at the inlet and outlet of the solid desiccant dehumidifier. These parameters were monitored using DHT11 and DHT22 sensors, as illustrated in the two figures below:

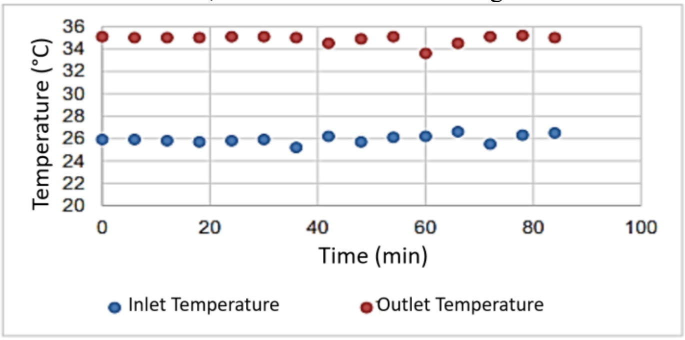

Fig. 7. Evolution of air temperature at the inlet and outlet of the dehumidifier

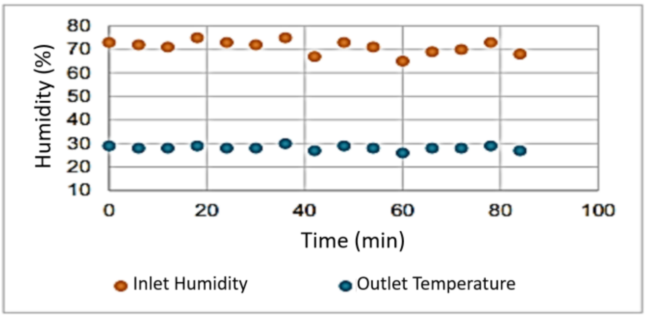

Fig. 8. Evolution of relative humidity of air at the inlet and outlet of the dehumidifier

B. Results of temperature regulation during different drying sessions

With our device, we conducted multiple drying sessions where we recorded temperatures in the drying chamber, representing them on a curve over time as follows:

1) Drying of carrots with a set temperature of 50°C:

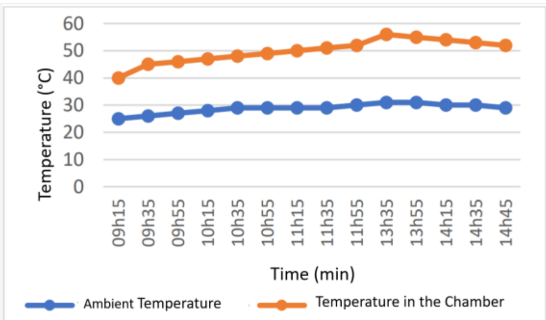

Fig.9. Variations in outdoor temperature and chamber temperature during carrot drying over time

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The temperature in the chamber is well-regulated as it remains close to 50°C, and after a drying time of 5 hours and 30 minutes, the carrots are dried with a final moisture content of 10%.

2) Drying of bananas with a set temperature of 60°C:

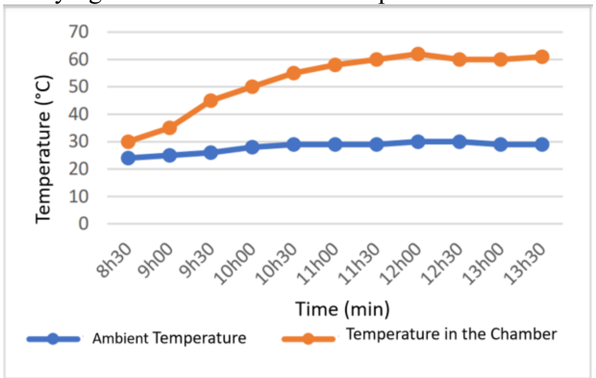

Fig.10. Variations in outdoor temperature and chamber temperature during banana drying over time

The temperature in the chamber is well-regulated as it remains close to 60°C, and after a drying time of 5 hours, the bananas are dried with a final moisture content of 20%.

C. Results of the Energy Sizing

To ensure the optimal functionality of the loads that need to be powered in Madagascar, considering the limited sunlight availability of 3.27 hours per day, the following are the obtained results and those currently accessible in the market:

TABLE III. RESULTS OF THE PHOTOVOLTAIC ENERGY SYSTEM SIZING

Designations	Symbols	Values
Peak power of PV	PC	22,95 ≈ 25 [W]
Battery capacity	C	*4,46≈ 5 [Ah]*
Regulator current	I_{reg}	*1,275 ≈ 5 [A]*

D. Final Result of the Experimental Prototype

The results obtained during the experimentation of the prototype are extremely promising. The device has demonstrated remarkable efficiency in the drying process using solar energy, with a significant reduction in the humidity of the incoming air and a notable increase in air temperature. The tests also confirmed the accuracy and reliability of the embedded electronic module for temperature regulation, as well as online data transmission. Additionally, the photovoltaic panel with the battery consistently provided the energy needed for the continuous operation of the system. These promising results validate the effectiveness of our technological approach in the field of solar drying. The visual representation of the prototype in Figure 11 below illustrates the different modules that compose our device.

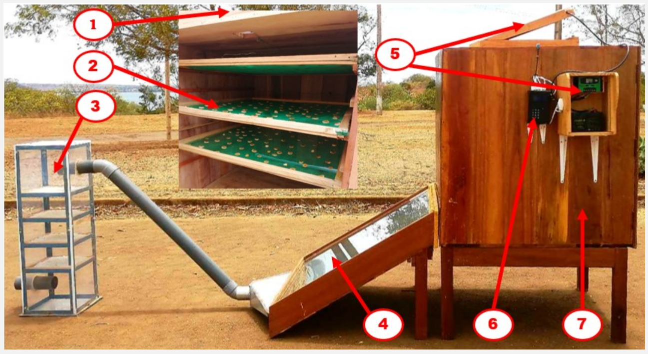

Fig. 11. Smart Mini Solar Dryer: Laboratory Pilot

The presented prototype was designed using local materials and electronic components provided by a local supplier. Furthermore, the interfaces were inclusively designed to facilitate usage by incorporating more images. Additionally, the application is equipped with voice assistance and sound signals to enhance the user experience.

E.Discussions

The presented work focuses on the design of a device that can be used for studying and optimizing the operation of various modules of an intelligent dryer. Its implementation allowed for studies to optimize the dehydration process by dehumidifying the air before dehydrating the food. Experimental results obtained from the solid adsorption dehumidifier module reveal that parameters such as relative humidity and air temperature were measured with a time difference of six minutes. Figures 7 and 8 show that the air temperature at the dehumidifier outlet increases while humidity decreases by 26%, validating that silica gel is a good moisture-absorbing material. However, this material remains expensive for farmers. Therefore, tests with a local product as a desiccant, such as rice, need to be conducted. On the two curves in Figures 9 and 10, the temperature captured by the BME280 sensor in the drying chamber is well regulated, as it is close to the set temperature for each type of dried food. Electronic sensors are powered by the photovoltaic panel, and the values measured by the sensors can be visualized and utilized by the application connected to the electronic box. This application includes an interesting voice option for users. It is also noted that several scientific disciplines (thermal, embedded electronics, energy, computer science, etc.) are involved in designing the modules of this device.

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Consequently, practical work in these different disciplines can be developed for teaching with each of the modules, leading to a wealth of data that research laboratories can exploit to continue optimizing the modules. This work was also motivated by child malnutrition in Madagascar, exacerbated by COVID-19. A recent study shows that 13% of children suffer from acute malnutrition, 50% suffer from anemia, and 53% of children under 5 years old have growth retardation. Local NGOs recommend spirulina, an excellent nutritional supplement, to address these issues. However, the current local production includes an energy-intensive drying process, making the cost high. The next steps of this work will focus on optimizing the drying of spirulina, especially low-temperature drying. The control of the device's temperature is not yet perfect. This parameter is crucial for spirulina drying, and the lack of control can degrade essential nutrients.

IV. CONCLUSION AND PERSPECTIVES

The study aimed to develop an experimental setup to design an intelligent solar dryer that would ensure the preservation of vitamins and sensitive nutrients in food. This setup consists of different modules. The dehumidifier module demonstrated the efficiency of silica gel as a desiccant material. The sizing of the energy system provided adequate power to the embedded electronic system and monitored production. Furthermore, the design of inclusive interfaces promotes visualization of the drying process evolution. The use of the application facilitates process monitoring and signals the end of drying. The results show that the intelligent solar dryer prototype allows for faster drying with a slight variation in the set temperature for a given type of food.

In perspective, it would be beneficial to explore methods to further optimize the energy efficiency of the intelligent solar dryer. This could include research on advanced insulation materials, more sophisticated energy management strategies, and the integration of technologies for more precise regulation. Digital tools will be developed for collecting environmental data for predictive studies using artificial intelligence (AI).

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