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Enhancing Grape Drying Efficiency: A Thermo-Ecological Analysis of a Hybrid Solar Greenhouse Dryer

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Abstract. Over the past few years, there has been a substantial increase in attention and notable interest in the utilization of solar energy for agricultural applications. This increased attention stems from the recognition of solar energy as a compelling and environmentally conscious alternative to conventional energy sources. Among the various applications, solar drying of crops has emerged as a promising method for preserving agricultural produce while minimizing energy consumption and reducing carbon emissions. In this study, our objective is to assess the thermo-economic and ecological performance of a solar-electric hybrid greenhouse dryer specifically designed for grape drying. The proposed system integrates solar collectors, an electric heater, and a greenhouse structure to create a controlled and energy-efficient environment for grape drying. The assessment includes a thorough analysis of the thermal performance, energy consumption, and cost-effectiveness of the solar-electric hybrid greenhouse dryer. Additionally, an ecological assessment is performed to assess the environmental impact of the system, considering factors such as carbon emissions and sustainability. The findings of this study are expected to have a significant impact on the advancement of sustainable agricultural practices and the widespread adoption of renewable energy technologies in the field of food production. Moreover, the obtained results serve as valuable insights for designing and optimizing similar solar drying systems intended for different crops and geographical regions. By considering specific crop characteristics and local environmental conditions, researchers and engineers can develop efficient and customized solar drying solutions. This knowledge will ultimately enhance the effectiveness and applicability of solar drying technologies, facilitating sustainable agricultural practices across diverse contexts.

Keywords. Agricultural greenhouse, solar drying, mixed mode, drying efficiency, energy analysis

1. Introduction

Morocco possesses abundant agricultural resources and plantations, which play a crucial role in the region's economic advancement. Thus, it is imperative to prioritize the preservation of plant quality and implement efficient post-harvest processing techniques to mitigate any potential decrease in commodity prices, protect the well-being of farmers,

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and ensure food security. However, the storage of harvested crops often results in reduced quality, necessitating the implementation of drying and dehydration techniques to address this challenge. In rural areas, solar energy is widely employed for drying agricultural products, taking advantage of Morocco's ample solar energy potential. However, utilizing solar energy for drying presents specific challenges due to its dependence on weather conditions. Furthermore, commodities that are stored without drying have a tendency to reabsorb moisture from the surrounding air, particularly during high humidity periods like nighttime, underscoring the significance of dehydration. Nevertheless, traditional open-air sun drying methods carry the risk of contamination from dust and insects, potentially compromising the quality and yield of the crops [1]. Indirect drying in a container represents an alternative approach that utilizes heat effectively to facilitate the drying of food in a controlled and hygienic environment, conforming to international standards. This method offers several advantages, including time and energy savings, reduced space requirements, enhanced product quality, and environmental sustainability. By adopting this approach, it is possible to achieve efficient food drying while promoting resource conservation and preserving the integrity of the environment. Solar dryers are classified into three distinct categories, which are determined by their energy usage and system layout. These categories include direct dryers [2], indirect dryers, and mixed dryers [3]. Modular dryers are commonly employed to process smaller quantities of fresh products and feature specialized designs. Greenhouse solar drying systems incorporate a combination of direct solar drying and mixed-mode drying methods. This hybrid approach is particularly employed during the peak summer period, when the agricultural greenhouse is converted into a solar dryer to optimize the drying process. Research has been undertaken to enhance the efficiency of the drying process utilizing solar energy and address the associated challenges.

Implementing heat storage mechanisms to sustain the drying process throughout the night or using another source of energy is a viable solution to improving the efficiency and effectiveness of drying processes. Heat storage systems can be used to capture excess heat during the day when the sun is shining and then release that heat at night to continue the drying process. This approach can be particularly effective in areas where the temperature drops significantly at night, which can slow down the drying process. Similarly, employing electricity as an alternative energy source can effectively sustain the drying process, even when there is insufficient sunlight. This approach can be particularly useful in areas where there is no access to other energy sources or where the cost of other energy sources is prohibitively high. In this context, the mixed-mode greenhouse solar dryer with automated control's thermal efficiency is investigated for grapes drying. The outcomes of this strategy are also contrasted with those of the conventional open-sun drying procedure.

2. Materials and Methods

2.1. The Greenhouse Solar Drying System Description

The system is composed of a cement base measuring 7.36 m^2 in area and having a volume of 22 m^3. Its framework is constructed using aluminum material, and the facades are covered with 0.006 m thick glass panels, as depicted in Figure 1. Located at the central portion of the greenhouse, the drying chamber has dimensions of 1.5 m in height, 0.63

m in width, and 0.8 m in length. To protect foods from ultraviolet rays that can degrade vitamins, the chamber is shielded with perforated black plastic, which also promotes air circulation within the drying trays. Additionally, an electric heater surrounds the chamber to provide warmth at night. The system incorporates a battery and a photovoltaic solar panel, which are responsible for powering the heater and the control unit.

Figure 1. Photo of the greenhouse solar dryer, with the drying process.

2.2. Removed Moisture Content

The essential drying parameter, referred to as the removed moisture content w_R, can be determined by dividing the mass of water in the product by the total mass of the product. The total mass of the product is obtained by summing the mass of water and the mass of a dry sample. This value is obtained through equation (1) [2]:

$$w_R = \frac{(w_{int} - w_o)}{w_{int}} \times 100 \quad (1)$$

where w_{int} and w_o represent the initial and final masses of the product after the drying process, respectively.

2.3. Experimental Protocol

To maintain a consistent grape size, the diameter was carefully controlled at 1.30 cm ± 0.1 cm. Prior to the drying process, the grapes underwent manual washing using potable water to eliminate any dust particles. A pre-treatment step involved briefly immersing the grapes in a hot water bath for 5 seconds, followed by rapid cooling in cold water. For the first experimental study, a forced convection greenhouse solar dryer was employed, equipped with an overnight heater unit to regulate the temperature within the drying chamber. A total of (500 ± 0.01) g of grapes were evenly distributed on a tray placed inside the drying chamber. Kipp and Zonen CMP11 pyranometers were employed to measure the global solar radiation both inside and outside the greenhouse. Additionally, HMP45C devices were deployed to monitor relative humidity and temperature at various locations within the greenhouse solar dryer. A control system was implemented to track indoor air relative humidity, indoor air temperature, and changes in weight. In the second experimental study, (500 ± 0.01) g of grapes were placed on a rack exposed directly to sunlight. The grape samples were dried until their moisture content reached a minimum of 30% (w.b.). To determine the average initial moisture content, the grape samples were subjected to oven drying at 100°C for 24 hours. Initial moisture content was found to be 70% ± 0.1%.

2.4. Assessing Greenhouse Solar Dryer's Carbon Footprint

The purpose of the environmental analysis is to assess the environmental impact of the developed system by quantifying its carbon footprint, particularly through the measurement of carbon dioxide CO_2 emissions. In particular, when the Moroccan electricity network is used as the energy source, the focus is on determining the extent to which the system has effectively reduced CO_2 emissions. To achieve this objective, a range of methodologies is required, as referenced in [2, 4, 5]. In the context of the solar greenhouse drying system, CO_2 emissions are generated by the heater unit and the control system, which consume energy. The calculation of CO_2 emissions in this study focuses specifically on those generated during the combustion process. For electricity-related emissions, the analysis incorporates the CO_2 emissions resulting from electricity generation in Morocco. It is important to note that Morocco's electricity generation relies heavily on fossil fuels, which account for over 80% of the energy mix [6].

The CO_2 emissions amount $AE(CO_2)$ is given by equation (2) [4]:

$$AE\ (CO_2)\ (g) = EC \times AEU\ (CO_2) \tag{2}$$

where AEU is the CO_2 amount emissions per energy unit (kg/kWh), and EC is the energy consumption (kWh), given by equation (3):

$$EC = P \times D_O \tag{3}$$

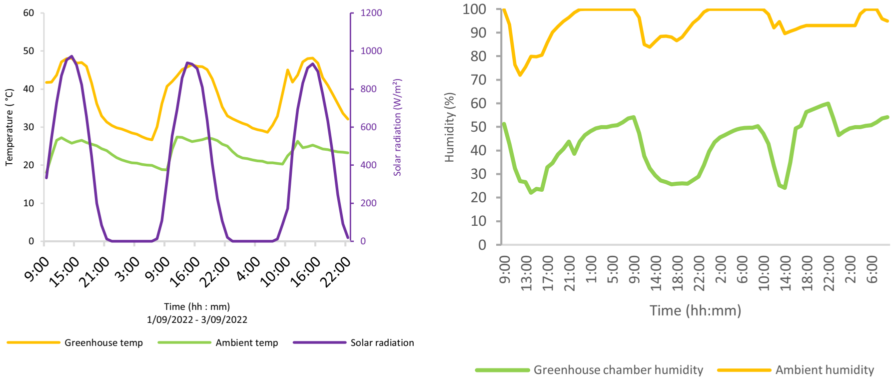
where P represents the nominal power (kW) of the energy system and D_O signifies the duration of operation in hours.

3. Results and Discussion

3.1. Thermal Performance Results

3.1.1. Temperature

Solar radiation plays a crucial role in the drying process as a climatic factor. The experiment conducted over three days reveals the fluctuation of solar radiation, with a peak of 975 W/m² observed at midday, as depicted in Figure 2a. These variations in solar radiation directly influence the surrounding air temperature. Inside the greenhouse solar dryer, temperatures ranged from 30°C to 48°C, while outside temperatures ranged from 17°C to 28°C throughout the drying period. Despite the higher temperature within the system compared to the external environment, the greenhouse dryer demonstrates remarkable efficiency. At night, the temperature stabilizes at approximately 30°C for both the oranges and the drying chamber, attributed to the inclusion of a heater unit system within the greenhouse solar dryer. In contrast, temperatures in the open sun drop below 19°C, which could potentially have a negative impact on the drying process.



(a) (b)

Figure 2. (a) Variation of ambient temperature, solar radiation, and temperature in the greenhouse solar drying system with time; (b) Variation of humidity in the greenhouse solar dryer and the ambient air in function of time.

3.1.2. Relative Humidity

Humidity is a vital parameter for evaluating the effectiveness of a drying system. In the case of the greenhouse solar dryer, the inclusion of a heater system enables a passive dehumidification process by raising the internal air temperature during the night. This feature effectively reduces the humidity levels within the dryer. Figure 3b illustrates the fluctuations in relative humidity within the greenhouse solar dryer and the surrounding ambient air, providing a comprehensive overview of these changes. During the night, the relative humidity inside the greenhouse solar dryer ranged between 42% and 54%. Conversely, the system's relative humidity reached a minimum of 22% during the daytime. Notably, the average relative humidity within the greenhouse solar dryer consistently remained 54% lower than that of the ambient air throughout the three-day drying period. This significant reduction in relative humidity highlights the remarkable efficiency of the greenhouse solar dryer in maintaining optimal drying conditions.

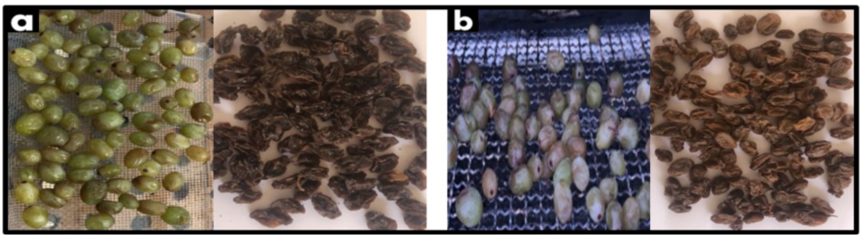


Figure 3. (a) Open drying of grapes (before & after); (b) grapes drying in the greenhouse solar dryer (before & after).

3.2. Drying Result

The drying time of a product is influenced by various factors, including the initial mass of the product, its initial water content, the drying temperature and rate, the temperature distribution within the drying chamber, and the prevailing climatic conditions. In this experiment, the mass of grapes decreased from 500 g to 125 g within a drying period of 15 hours in the greenhouse dryer. In contrast, achieving the same level of drying performance (with the same quantity of grapes) in the open sun dryer required 3 days. These findings, as presented in Table 1, demonstrate the competitiveness of these results compared to other studies on grape drying.

Table 1. Comparison of the drying speed of different varieties of solar dryers.

Ref.	**Types of solar dryers**	**Quality of grapes (Final moisture content)**	**Convection mode**	**Duration of drying**
[5]	Indirect natural convection dryer with chimney	26%	Natural	7-8 days
[6]	Indirect forced convection solar dryer with sensible heat storage material	18.5%	Forced	17h
[7]	Mixed-mode greenhouse solar dryer	18%	Forced	50h
[8]	Dish type solar collector dryer	17%	Forced	21h
Present study	Electric hybrid greenhouse dryer	20%	Forced	15h
	Open sun	20%	Natural	3 days

3.3. Assessing the Environmental Impact of the Solar Greenhouse Dryer

The system's nightly heating unit requirement averages around 9 kWh, resulting in approximately 1290 g of CO_2 emissions when powered by the Moroccan electrical grid. However, as the system is backed by renewable energy sources like photovoltaic panels, it has a beneficial environmental impact. In fact, the system is entirely sustainable and emits no emissions.

4. Conclusion

The grape drying process is a crucial step in winemaking, and its efficiency and quality are directly related to the final product's taste and aroma. Utilizing solar energy for grape drying offers numerous benefits, including lowered energy expenses, enhanced energy efficiency, and diminished greenhouse gas emissions. In this research, a novel Solar-Electric Hybrid Greenhouse Dryer was designed, constructed, and tested to assess its effectiveness and efficiency in grape drying. Experimental tests were conducted using forced and natural convection to evaluate the dryer's performance. Results indicated that the hybrid greenhouse solar dryer was significantly more efficient than the open-sun method in terms of drying time, with a reduction of approximately 2.5 days. Overall, the findings of this investigation showcase the viability of solar energy for sustainable agricultural practices, particularly in the field of grape drying. The Solar-Electric Hybrid Greenhouse Dryer is a promising technology that can help reduce the environmental impact of winemaking while also providing economic benefits to farmers and winemakers.

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