ENERGY QUIPSYS

Energy Equipment and Systems

ENERGY EQUIPMENT
AND
SYSTEMS

An experimental assessment of a portable solar cabinet photovoltaic dryer utilizing parsley greens: A case study

Manuscript Type
Research Paper

Authors

Mojtaba Moravej[a]
Hamid Mozafari[a*]
Farshad Ebrahimpour[b]
Reza Hosseini-Ara[a]

[a] Mechanical Engineering Department Payame Noor University, Tehran, Iran

[b] Agriculture Department Payame Noor University, Tehran, Iran

ABSTRACT

This paper presents the experimental testing of a portable double solar dryer developed by the authors. The dryer's primary feature is its ability to facilitate direct heat transfer from sunlight, complemented by forced airflow generated by a photovoltaic fan. The material dried in this study was parsley, with tests conducted during the spring of 2024 in Khuzestan Province, southern Iran. The main objective of this research is to address the issue of non-uniform drying rates of products within the drying tray. The investigation assessed the device's efficiency and performance under varying conditions of heat and mass transfer. Environmental parameters, including sunlight, air temperature, humidity, and wind speed, were meticulously measured throughout the testing period. Results indicated that the average drying efficiency for parsley was 21.55%, with a maximum drying speed also recorded at 21.55%. Furthermore, the findings demonstrate that the dryer exhibits acceptable performance across different heating conditions. An analysis of weather conditions, including temperature, humidity, and solar radiation, revealed that increased air temperature and radiation significantly reduce drying time while enhancing dryer efficiency, which can reach approximately 37.9%. The uncertainty level of this research is calculated to be less than 5%.

1. Introduction

Recent climate changes and widespread environmental pollution caused by the consumption of fossil and nuclear energy have led to a growing interest in renewable energy sources. While the reliance on fossil and

* Corresponding author: Hamid Mozafari
Mechanical Engineering Department Payame Noor University, Tehran, Iran
Email: Mozafari.h@pnu.ac.ir

nuclear fuels has also resulted in political and social challenges, the adoption of renewable energy is increasingly supported by governments worldwide, with many countries offering incentives and support packages. This shift has prompted researchers globally to prioritize the exploration of various renewable energy options. Among these, solar energy holds a particularly prominent position and has been a focal point of human interest for many years. Today, solar energy is harnessed in two

primary forms: thermal and photovoltaic [1-3]. In thermal systems, heat from solar radiation is harnessed directly or indirectly for various applications, including power plants, water heaters, and collectors. One of the most significant applications of solar thermal systems is in drying technologies. Solar dryers utilize solar radiation to dry a variety of materials, particularly in the food and agricultural sectors. Based on their drying mechanisms and design features, solar dryers can be categorized and constructed in various ways; however, a key focus across all designs is their performance and efficiency. Numerous scientists have researched solar dryers [4-5].

In a comprehensive study on the applications of low-temperature solar collectors, different collector models were discussed, with solar dryers identified as one of the most important applications within this category [6]. Additionally, an intriguing study investigated the use of vacuum tube collectors in a solar dryer. In this research, grapes were dried, resulting in a reduction of moisture content from 78% to less than 10% within just 14 hours [7].

In a practical study, the performance of a solar dryer for red pepper was analyzed. This research demonstrated that approximately 70% of the red pepper was dried within 33 hours, with the efficiency of the solar collector and dryer reported at 28% and 13%, respectively [8]. Additionally, another study introduced a new model for a solar dryer that integrates photovoltaic cells and a vacuum tube collector for agricultural products. The evaluation included both technical efficiency and economic analysis. The results indicated that the overall efficiency of the system exceeds 34%, and the payback period for the investment is relatively short [9].

In an experimental study, cut leaves dried in a solar dryer utilizing phase change materials demonstrated a 55% reduction in drying time compared to whole leaves. Additionally, the use of phase change materials further decreased the drying time compared to systems that did not incorporate them [10]. Another study, combining experimental and computational methods, investigated an indirect flow solar dryer with iron grids. The findings revealed an increase in efficiency due

to the double passage of air through the iron networks, achieving the highest average yield of 23.08% [11].

In an interesting model of a passive hybrid solar dryer for tomato drying, the results showed that the temperature inside the dryer chamber at solar noon was close to 70 °C, and the efficiency of the dryer was about 52-55% [12]. In a research, an indirect solar dryer using a rock solar energy storage system was studied. The results showed that the temperature difference between the output of the collector and the ambient temperature in the evenings was more than 7°C, which was suitable for drying [13].

In the mathematical modeling of a forced flow solar dryer, several models were evaluated, including the Newton, Page, Henderson, and Wang-Wing models. The results indicated that the Page model was the most suitable for construction and experimental testing, with a proposed flow rate of 0.009 kg/s [14]. In another study, a solar cabinet dryer designed for grapes was assessed, and various models were evaluated to predict the optimal drying time. The analytical estimate for the drying time was 52 hours, while the experimental tests recorded drying times of up to 56 hours [15].

The design, construction, and performance evaluation of a solar dryer utilizing a vacuum tube collector for drying garlic were conducted in this study. The collector used in this research had an area of 1.34 m² and featured 15 risers, with an air flow rate of 3.7 m/s. The results indicated that the average drying rate was 0.81 kg of water evaporated per kg of drying material per hour [16].

An experimental study comparing direct and indirect drying methods for cranberries in a solar dryer demonstrated that the indirect solar dryer system outperformed both the open and direct drying methods [17]. Additionally, a laboratory investigation into heat transfer within a solar dryer for drying carrot pieces, specifically those with a diameter of 3 mm, led to the development of an equation that describes the displacement heat transfer coefficient in the dryer. The validity of the resulting equations was confirmed through simulations conducted using COMSOL software [18].

One significant barrier to the widespread adoption of solar drying systems is the complexity and high cost of the devices. In this research, a dual-purpose portable solar dryer was designed and manufactured by the authors. This dryer utilizes direct sunlight for heating and employs photovoltaic fans to create a forced airflow over the drying materials. To assess the thermal performance and mass transfer capabilities of the device, parsley, an edible vegetable, was selected as the test material.

This research introduces several novel contributions to the field of solar drying technology, particularly for agricultural products. The key novelties of this study are:

- Development of a Portable Double Solar Dryer: This study presents a unique design of a portable solar dryer that enhances the versatility and accessibility of solar drying for small-scale farmers in varying geographical locations.
- Integration of Photovoltaic Fan Technology: The innovative incorporation of a photovoltaic fan facilitates forced airflow, significantly improving the drying efficiency and uniformity by enhancing heat transfer within the drying chamber.
- Empirical Analysis of Parsley Drying Efficiency: The paper provides extensive experimental data on drying parsley, offering insights into the impacts of varying environmental conditions on drying efficiency, with recorded average efficiencies of 21.55% and peak performance approaching 37.9%.
- Comprehensive Environmental Monitoring: Through meticulous measurements of environmental parameters such as sunlight intensity, air temperature, humidity, and wind speed during the drying process, this study establishes a detailed understanding of the factors influencing the performance of solar dryers in real-world scenarios.

These contributions provide crucial insights into optimizing solar drying systems and address the ongoing challenges in achieving energy-efficient and sustainable agricultural practices.

Nomencalture

|	
A	Surface area (m^2)
E_{in}	Inlet energy (W)
G_T	Sun radiation (W/m^2)
M_o	Initial humidity (gr)
M_R	Humidity ratio
M_t	Instantaneous humidity (gr)
Q_u	Output energy (W)
Q_L	Water latent heat of evaporation (W)
R	Evaporation rate (gr/min)
S_η	Uncertainty
T_a	Ambient temperature (^{0}C)
w	Mass of evaporated humidity (kg)
η_i	Efficiency

2. Materials and methods

The device utilized in this research is a portable and practical solar dryer, specifically designed and constructed by the authors in Khuzestan Province, located in the southern region of Iran. This innovative dryer has undergone rigorous testing and evaluation to assess its performance and efficiency. Figure 1 illustrates the laboratory arrangement of the test materials and the solar drying apparatus. The configuration showcases the integration of the dryer with the test materials, facilitating a comprehensive assessment of the drying process.

The specifications of the solar collector and the drying chamber are detailed in Table 1. This table includes critical parameters such as dimensions, materials, and thermal efficiency, providing a clear overview of the system's design. Table 2 outlines the specifications of the measuring devices employed in the study, including their accuracy and calibration details. These instruments are essential for monitoring temperature, humidity, and airflow within the dryer, ensuring precise data collection throughout the experiment.

The primary drying material used in this study is parsley, which was selected for its nutritional value and common usage. The parsley is placed in a mesh tray within the dryer, as depicted in Fig. 2. This design allows for optimal airflow and uniform drying, enhancing the overall efficiency of the drying process.

Table 1. Characteristics of the tested dryer

Specifications	Materials and dimensions
Dry geometry	Cubic geometry with trapezoidal cross-section
Dry dimensions	700*445*600 mm
Chamber	285*95*60 mm
Glass wall	Flat glass with a thickness of 6 mm
Set weight	14 kg
Photovoltaic panel	Panel with dimensions of 10 W
Fan	Two fans with a diameter of 120 mm
Volume of drying material	Maximum 0.162 m^3
Area	720*340 mm
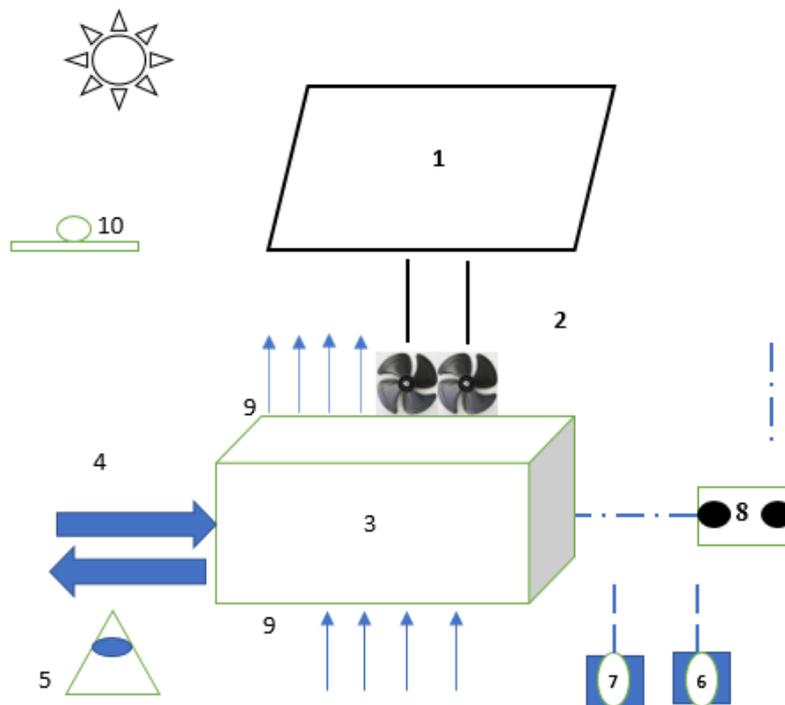
1	Solar panel	3	Dryer chamber	5	Scales	7	Humidity meter	9	Air vent
2	Fans	4	Access door	6	Wind speed meter	8	Thermometer	10	Solar meter

Fig. 1. Schematic of the experimental setup

Table 2. Measuring devices

Device name	Model	Accuracy	unit
Radiation meter	VoltCraft-slx 300	1	W/m^2
Anemometer	Lutron	0.1	m/s
Temperature data logger	Kimo	0.1	^{0}C
Humidity meter	DC103	1	%
Scales	SF-400	1	gr

Fig. 2. Photovoltaic cabinet dryer drying parsley

2.1. Test method

To collect data, all measuring devices were first calibrated, followed by the setup of the laboratory arrangement as depicted in Fig.1. The experiments were conducted in the spring of 2024 (May 2024), using edible parsley as the drying material, as shown in Figure 2. After the drying process, measurements were taken for wind speed, air humidity, and ambient temperature.

The dryer compartment is designed as a removable drawer, facilitating easy access to the drying materials. Once the dryer is positioned in direct sunlight, the fans automatically activate, creating airflow that passes beneath the material tray before exiting through the side of the fans. Concurrently, direct solar radiation on the parsley, facilitated by a glass wall, promotes enhanced moisture evaporation.

The experiments were conducted multiple times, with data recorded at regular intervals throughout each trial. The change in the mass of the parsley, corresponding to the loss of moisture, served as the primary measure of drying efficacy.

2.2. Governing equations

Basically, vegetable dryers are a type of thermal systems that consist of a heat exchanger and a mass transfer system. Heat transfer in them causes mass transfer. In solar dryers, the source of heat transfer is solar radiation, and the meaning of mass transfer is the transfer and removal of moisture from drying materials. To evaluate these systems, you can use the efficiency criteria and the amount of functional efficiency for them.

The efficiency for any heating system can be considered as Eq. (1) [9]:

$$\eta = \frac{Q_u}{E_{in}} \tag{1}$$

where Q_u is the useful heat obtained, E_{in} is equal to the total energy, and η is the efficiency rate. Also, the efficiency of the drying chamber is equal to the energy received from it; that is, the amount of heat that causes the moisture of the drying material to evaporate is equal to the amount of solar energy received. Using Eq. (2), the efficiency of the whole solar dryer set is calculated [9].

$$\eta = \frac{wQ_L}{E_{in}} \tag{2}$$

where w is equal to the mass of evaporating moisture and Q_L is the latent heat of water evaporation. If in relation (2) the input energy to the system is considered equal to the total energy consumption of photovoltaic fan electricity and solar radiation, then Eq. (3) can be written instead.

$$\eta = \frac{wQ_L}{AG_T} \tag{3}$$

where G_T is the radiation reaching the dryer and A is equal to the total area of the glass wall (that is, the passage of light and radiation reaching the material) plus the area of the solar panel. Also, to evaluate the drying kinetics, the humidity ratio variable is introduced according to Eq. (4) [9]:

$$M_R = \frac{M_t - M_e}{M_o - M_e} \tag{4}$$

where Me is the equilibrium moisture content, Mt is the moisture content at any moment and Mo is the initial moisture content. Due to the smallness of Me, it is omitted in the equation and therefore the humidity ratio is presented according to Eq.(5) [9]:

$$M_R = \frac{M_t}{M_o} \tag{5}$$

Therefore, by having the humidity ratio, it is possible to evaluate the drying rate of the product at any moment.

2.3. Uncertainty analysis in experimental experiments

It is obvious that conducting any experiment and investigation is associated with error; but what is important is the amount of error in the results, which makes it possible to determine the reliability of the results while presenting the accuracy of the researcher. In order to check the accuracy of the research, the method of uncertainty analysis can be used. One of the criteria for determining the uncertainty of the method is to use the sum of squares or RSS, which is presented in relation (6) [1, 19].

$$S_U = \left(\sum_{i=1}^{n} \left[S_{x_i} \frac{\partial U}{\partial x_i} \right] \right)^{\frac{1}{2}} \tag{6}$$

If the evaluated function is a multiple of independent data, then the uncertainty of this function will be in the form of Eq. (7) [19].

$$S_U = \sqrt{\left(a\frac{S_1}{x_1} \right)^2 + \left(b\frac{S_2}{x_2} \right)^2 + \ldots + \left(N\frac{S_n}{x_n} \right)^2} \tag{7}$$

According to the effective quantities in the efficiency, which include mass, time and solar radiation, Eq.(6) can be written as Eq. (8) [19].

$$S_\eta = \sqrt{\left(\frac{\Delta\dot{m}}{\dot{m}} \right)^2 + \left(\frac{\Delta Dt}{Dt} \right)^2 \left(\frac{\Delta G_T}{G_T} \right)^2} \tag{8}$$

To enhance the understanding of the performance of the portable solar cabinet photovoltaic dryer, we conducted a comprehensive analysis using MATLAB software. This analysis allowed us to model the drying process of parsley greens and analyze key parameters such as temperature, humidity, and drying rate in relation to experimental data. By integrating the results from the MATLAB simulations into our discussion, we provide valuable insights that elucidate the effectiveness of the drying system. This approach not only underscores the relevance of computational modeling in conjunction with experimental assessments but also strengthens the findings presented in this study. According to the study of uncertainty and measurement error, the uncertainty for material mass, time, and solar radiation is 1%, 2.25%, and 4.1%, respectively, and the total uncertainty, S_η, in this research is 4.47%.

3. Results and Discussion

As mentioned, the experiments were repeated in different conditions and on different days, and the data were prepared and reported in clear and dust-free air. To test, a certain amount of fresh parsley is first weighed and placed in a drying chamber. In order to evaluate more accurately, the data were examined during the experiment period, and repeated data were collected and displayed. Figure 3 shows the amount of solar radiation reaching the dryer during the experiment. According to the test interval, before solar noon, the trend of radiation will be upward, and after it reaches its maximum value at noon, it will have a downward trend in the afternoon.

In Fig. 4, during the experiment, the amount of humidity in the ambient air and the wind speed at that moment are recorded. In this graph, it is clear that the atmospheric conditions were relatively stable until 16:48, and both the wind speed and the relative humidity of the air are uniform and with little changes during several hours. After the mentioned hour, both wind speed and humidity have changed and both have taken an upward trend until the end of the experiment. In fact, when the solar radiation is decreasing, these two parameters of wind speed and humidity have increased, and according to graph 4, the rising rate of humidity is higher than the of wind speed. In Fig. 5, the ambient air temperature during the experiment has been collected and plotted. According to this figure, with the increase of radiation, the temperature of the air continuously increases and reaches its maximum value in the afternoon, and continues its downward trend after that.
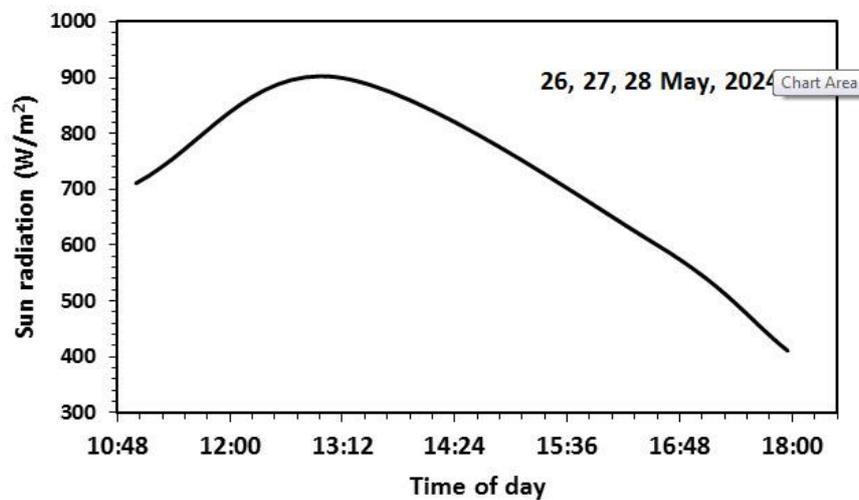
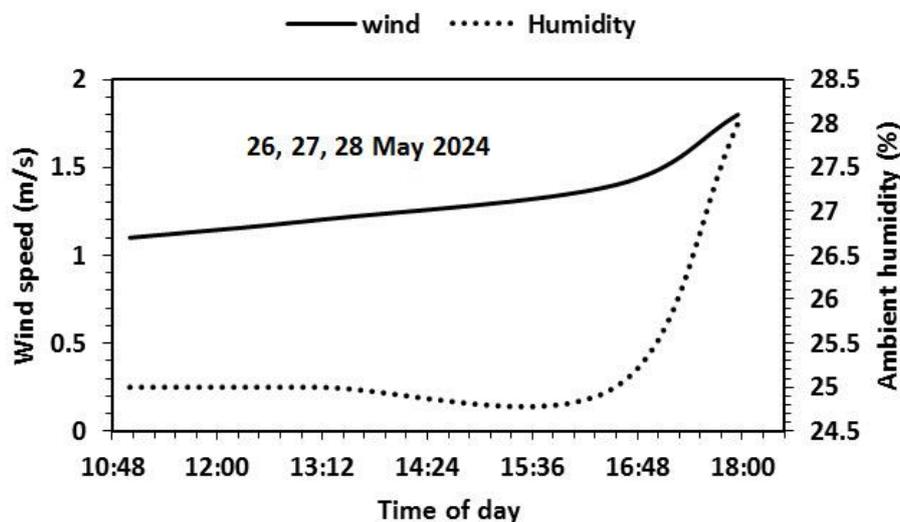**Fig. 3.** Amount of solar radiation during the experiment

Fig. 4. Wind speed and ambient humidity during the experiment
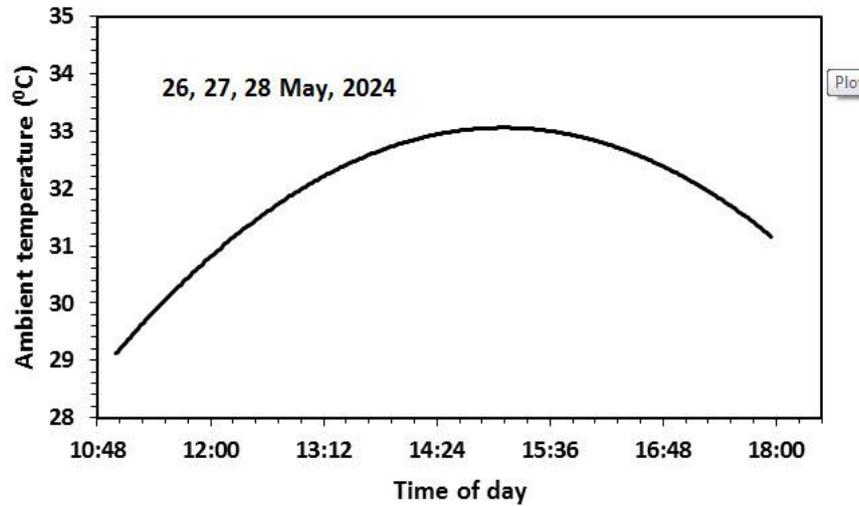
Fig. 5. Ambient air temperature diagram during the experiment

Figure 6 illustrates the changes in moisture content of the parsley during the experiment. The graph exhibits a relatively steep slope throughout the duration of the drying process, indicating a significant reduction in moisture content over time. This trend is expected, as initial moisture levels in fresh parsley are typically high, resulting in rapid moisture loss during the early stages of drying.

Figure 7 presents the mass of the drying material over the course of the experiment. The data clearly demonstrate a decrease in mass as time progresses, with a more pronounced decline observed in the initial phase compared to the later stages. This initial steep slope can be attributed to the high surface moisture present in the parsley leaves, leading to a rapid rate of evaporation during the early drying period. As the drying process continues, the rate of mass loss gradually decreases, resulting in a milder slope on the graph. In Fig.7, the relationship between the mass of the drying material and ambient temperature is depicted. The graph indicates that as the air temperature increases, the relative humidity decreases, which is a typical behavior in drying processes. This inverse relationship highlights the importance of temperature in facilitating moisture evaporation, thereby enhancing the efficiency of the drying operation.
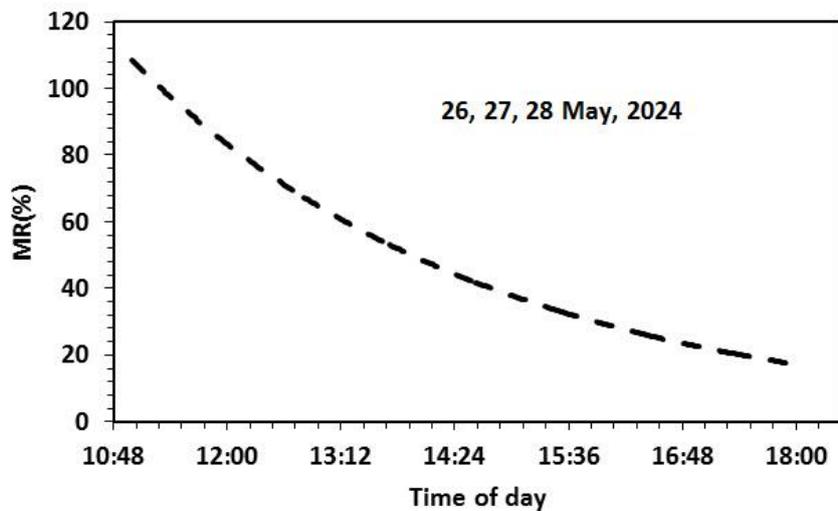

Fig. 6. Changes in the humidity ratio of parsley during the experiment
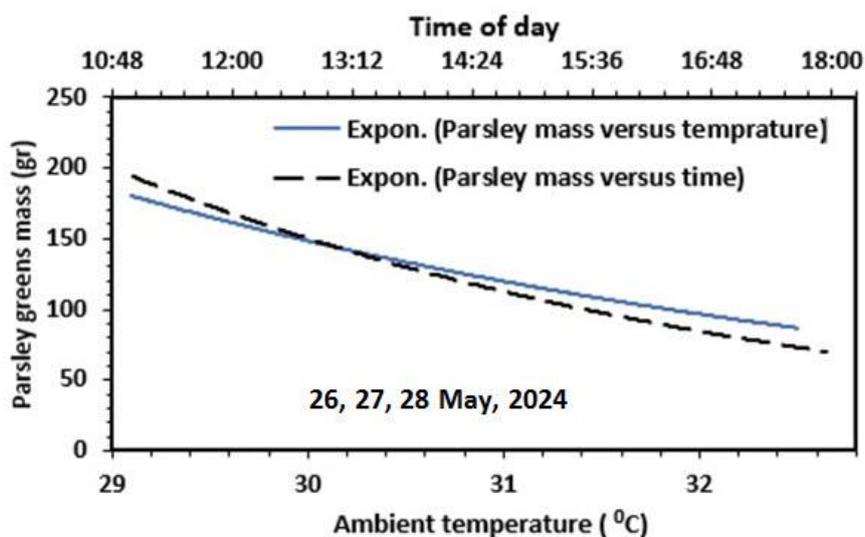
Fig. 7. Changes in mass of parsley during the experiment

In general, the air conditions—including temperature, humidity, and sunlight—were evaluated and presented in Figs. 3 through 7. The data indicate that the effect of air humidity on dryer efficiency was minimal, as evidenced by a Pearson correlation coefficient of approximately -0.27 between relative air humidity and dryer efficiency. This statistical analysis suggests that while humidity does influence the drying process, its impact is relatively small. The negative correlation coefficient further implies that as humidity an increases, the drying process slows down, which aligns with established drying principles. Additionally, the correlation coefficient between wind speed and dryer efficiency was found to be less than 0.1, indicating a weak relationship. Although wind speed is generally known to facilitate drying by enhancing evaporation, the lack of significant changes in wind speed—particularly during the initial stages of the drying process—likely influenced this trend. This observation highlights the importance of consistent airflow in optimizing dryer performance; however, the limited variation in wind speed during the experiments may have masked its potential effects on drying efficiency. Overall, these findings underscore the complex interplay between environmental factors and drying performance, suggesting that while certain conditions like humidity and wind speed play roles in the drying process, their effects can be moderated by other variables present during the experiment.

Figure 8 illustrates the moisture evaporation rate, denoted as R, which represents the drying speed derived from the experimental data. At the onset of the drying process, the drying rate is zero, corresponding to an initial humidity level of 100%. As time progresses, the drying rate increases and eventually stabilizes, reaching a relatively constant state of equilibrium. This behavior highlights a fundamental principle of drying: the rate of moisture evaporation is inversely proportional to the amount of moisture present in the material . As moisture content decreases, the driving force for evaporation diminishes, leading to a gradual reduction in the drying speed. This relationship is further quantified by the concept of equilibrium moisture content, which is defined mathematically in Eq. (5). Figure 9 presents this equilibrium moisture content, illustrating how it varies with time and correlates with the drying process . The data depicted in these figures underscore the dynamic nature of moisture evaporation during drying. Understanding this relationship is crucial for optimizing drying conditions and enhancing the efficiency of the drying process.
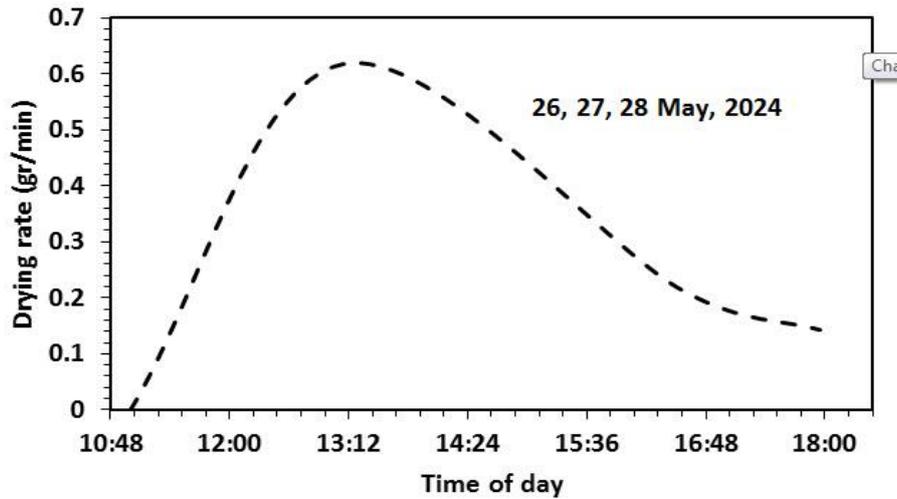
Fig. 8. Evaporation rate diagram (R) of humidity during the experiment

Figure 9 illustrates the moisture ratio (MR) during the drying process throughout the experiment. Vegetables typically exhibit high initial moisture content, resulting in a relatively steep slope on the drying graph. Notably, the data indicate that within just a few hours, a remarkable 75% reduction in moisture content can be achieved, highlighting the efficiency of the drying method employed.

Figure 10 presents the efficiency of the solar dryer during the experiment, while Fig. 11 depicts the dryer's efficiency in relation to solar radiation levels. Analysis of these figures reveals that the highest solar radiation—and consequently, the peak efficiency—occurred around solar noon. However, it is important to note that while the heat intensity is maximized at this time, the moisture content of the vegetables also plays a crucial role in determining overall dryer efficiency. The moisture level tends to be highest around solar noon, which can influence the drying rate and efficiency calculations.

Additionally, Table 3 provides a comparative analysis of the results from this research with findings from previous studies. This comparison not only contextualizes the current results within the broader body of research but also underscores the advancements made in solar drying technology.
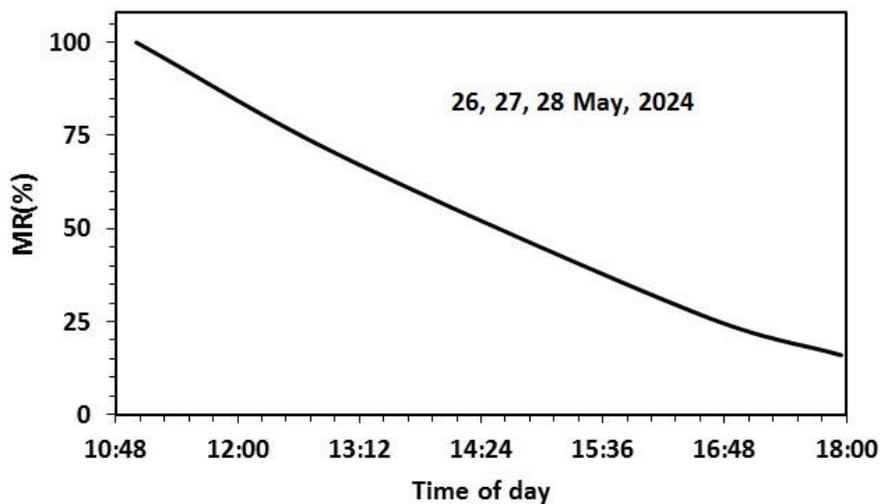

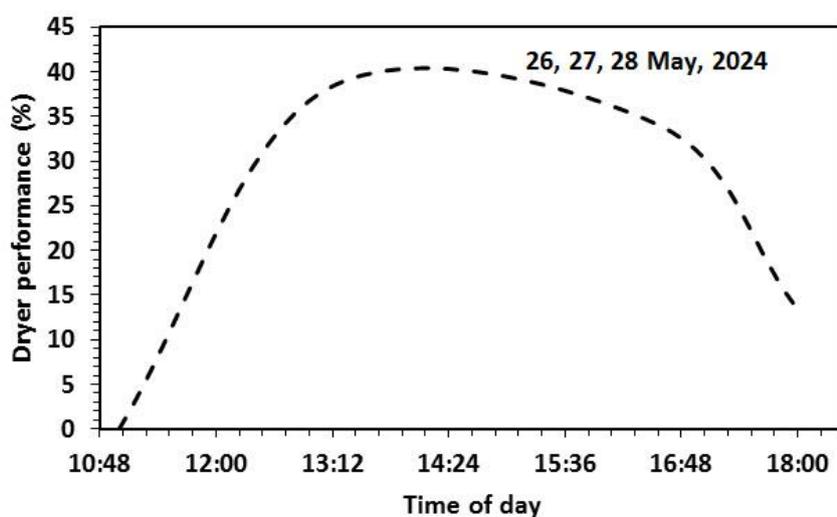**Fig. 9.** Moisture ratio of parsley during the experiment

Fig. 10. Thermal efficiency diagram of the solar dryer during the experiment
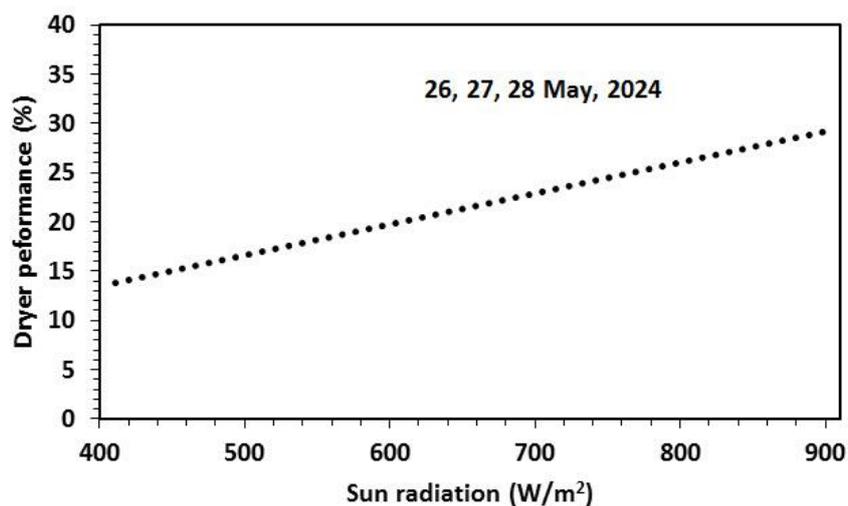

Fig. 11. The amount of yield changes based on the solar radiation

Table 3. Comparison of the results of the present study with previous experimental studies of solar dryers

Researcher	Type of device and type of drying material	Dry function
Ndukwu et al. [20]	Drying potatoes	efficiency between 25.31 and 31.5%
Simo et al. [21]	Drying firewood	The average yield during the year is 38.5%.
Lingayat et al. [22]	Indirect drying of watermelon and apple	The average yield is 28.76% for watermelon and 25.39% for apple
Gupta et al. [23]	Novel P-T solar dryer for carambola	Efficiency about 15.27%
Mugi & Chandramohan [24]	Direct and indirect drying of guava slices	Efficiency 26.19%
The present research	Parsley vegetable double cabinet dryer	The average efficiency 21.55%

In addition to its technical performance, the economic viability of the portable solar cabinet photovoltaic dryer is an essential consideration for potential users, particularly in regions where agricultural products are abundant but often suffer from post-harvest losses. The initial investment in the construction of the dryer is significantly lower compared to conventional electric or fossil fuel-powered drying systems. Furthermore, the utilization of a photovoltaic fan eliminates ongoing energy costs associated with electricity consumption, making it an attractive option for small-scale farmers and producers. The ability to dry parsley efficiently when solar radiation is available can lead to increased marketability and reduced spoilage, potentially translating into higher revenue for farmers. Considering the average drying efficiency of 21.55% and maximum performance observed at 37.9%, the system not only boosts production but also supports sustainability by reducing reliance on non-renewable energy sources. These economic benefits highlight the importance of adopting such solar drying technologies, particularly in arid and semi-arid regions where solar energy is abundant.

4. Conclusion

The utilization of solar air heaters is a prevalent practice in solar dryer systems that employ forced airflow. This method effectively facilitates the evaporation of moisture by passing heated air over the drying materials. In this research, we conducted an experimental evaluation of a solar dryer specifically designed for vegetables, employing a direct drying approach. This system utilized forced airflow generated by photovoltaic fans in conjunction with direct sunlight within the drying cabinet.

Our investigations focused on several key aspects, including the thermal performance of the dryer, the processes of mass and moisture transfer, and the influence of various environmental factors. The results revealed that the average efficiency of the solar dryer was 21.55%. Notably, this efficiency peaked at 37.9% under conditions of maximum solar radiation and elevated ambient air temperatures, demonstrating the significant

impact of these factors on drying performance. Additionally, we assessed the air conditions—specifically temperature, humidity, and solar radiation. The analysis indicated that air humidity and wind speed had minimal effects on the drying process, as evidenced by a correlation coefficient of less than 0.27. Conversely, the data showed a strong relationship between air temperature and solar radiation; as the temperature increased, the duration of time that the drying materials remained in the dryer was significantly reduced. These findings underscore the importance of optimizing environmental conditions to enhance the efficiency of solar drying systems. Future research could explore additional variables, such as different types of vegetables or alternative configurations of solar dryers, to further improve performance and broaden the applicability of solar drying technologies.

References

[1] Moravej M. An experimental study of the performance of a solar flat plate collector with triangular geometry. Journal of Solar Energy Research. 2021;6(4):923-36.

[2] Larki AJ, Ghafouri A, Assareh E, Moravej M. Investigation of the effects of the detachable vortex generators series on phase change material behavior in an energy storage system. Journal of Building Engineering. 2022;52:104384.

[3] Pambudi NA, Nanda IR, Putri AE, Salsala RN, Aziz M, Rudiyanto B, et al. An experimental investigation of various trickle collector structures to enhance solar water heater efficiency. Cleaner Engineering and Technology. 2024;21:100789.

[4] Duffie JA, Beckman WA, Blair N. Solar engineering of thermal processes, photovoltaics and wind: John Wiley & Sons; 2020.

[5] Kumi PGK, Elolu S, Odongo W, Okello C, Kalule SW. Where is the market? Assessing the role of dryer performance and marketability of solar-dried products in acceptance of solar dryers amongst smallholder farmers. Heliyon. 2023;9(8).

[6] Ahmadi A, Ehyaei M, Doustgani A, Assad MEH, Hmida A, Jamali D, et al. Recent residential applications of low-temperature

solar collector. Journal of Cleaner Production. 2021;279:123549.

[7] Salhi M, Chaatouf D, Bria A, Amraqui S, Mezrhab A. Experimental assessment of a new prototype solar dryer integrated with a photovoltaic system. Energy for Sustainable Development. 2024;81:101518.

[8] Fudholi A, Sopian K, Yazdi MH, Ruslan MH, Gabbasa M, Kazem HA. Performance analysis of solar drying system for red chili. Solar Energy. 2014;99:47-54.

[9] Singh S, Gill R, Hans V, Singh M. A novel active-mode indirect solar dryer for agricultural products: Experimental evaluation and economic feasibility. Energy. 2021;222:119956.

[10] Bareen A, Dash S, Kalita P, Dash KK. Experimental investigation of an indirect solar dryer with PCM-integrated solar collector as a thermal energy storage medium. Environmental Science and Pollution Research. 2024;31(12):18209-25.

[11] Güler HÖ, Sözen A, Tuncer AD, Afshari F, Khanlari A, Şirin C, et al. Experimental and CFD survey of indirect solar dryer modified with low-cost iron mesh. Solar Energy. 2020;197:371-84.

[12] César L-VE, Lilia C-MA, Octavio G-V, Isaac PF, Rogelio BO. Thermal performance of a passive, mixed-type solar dryer for tomato slices (Solanum lycopersicum). Renewable Energy. 2020;147:845-55.

[13] GaneshKumar P, Sundaram P, Sathishkumar A, Vigneswaran V, Chopra T, Thakur U, et al. Exploring the performance of an indirect solar dryer by combining three augmentation approaches (trapezoidal absorber, shot blasting, and pebble stone). Journal of Energy Storage. 2024;78:110109.

[14] Subbian V, Murugavel KK, Raja RS, Shanawaz A. Experimental investigation and the performance evaluation of a mixed mode solar dryer for coconut. Materials Today: Proceedings. 2021;45:3662-5.

[15] Komble S, Kulkarni GN, Sewatkar C, editors. Experimental investigation of solar drying characteristics of grapes. Proceedings of the 7th international conference on advances in energy research; 2020: Springer.

[16] Malakar S, Arora VK. Experimental Investigation of Evacuated Tube Solar Air Collectors for Drying Application. Recent Advances in Mechanical Engineering: Select Proceedings of ITME 2019: Springer; 2020. p. 395-404.

[17] Atia A, Teggar M, Laouer A. Performance of various solar dryer types integrating latent heat storage for drying agricultural products: An up-to-date review. Journal of Energy Storage. 2024;102:114048.

[18] Nettari C, Boubekri A, Benseddik A, Bouhoun S, Daoud D, Badji A, et al. Design and performance evaluation of an innovative medium-scale solar dryer with heat recovery based-latent heat storage: experimental and mathematical analysis of tomato drying. Journal of Energy Storage. 2024;88:111559.

[19] Moravej M, Noghrehabadi A, Esmaeilinasab A, Khajehpour E. The effect of SiO2 nanoparticle on the performance of photovoltaic thermal system: Experimental and Theoretical approach. Journal of Heat and Mass Transfer Research. 2020;7(1):11-24.

[20] Ndukwu M, Onyenwigwe D, Abam F, Eke A, Dirioha C. Development of a low-cost wind-powered active solar dryer integrated with glycerol as thermal storage. Renewable Energy. 2020;154:553-68.

[21] Simo-Tagne M, Ndukwu MC, Azese MN. Experimental modelling of a solar dryer for wood fuel in Epinal (France). Modelling. 2020;1(1):3.

[22] Lingayat A, Chandramohan V, Raju V, Kumar A. Development of indirect type solar dryer and experiments for estimation of drying parameters of apple and watermelon. Thermal Science and Engineering Progress. 2020;16:100477.

[23] Gupta A, Das B, Biswas A, Mondol JD. Sustainability and 4E analysis of novel solar photovoltaic-thermal solar dryer under forced and natural convection drying. Renewable Energy. 2022;188:1008-21.

[24] Mugi VR, Chandramohan V. Comparison of drying kinetics, thermal and performance parameters during drying guava slices in natural and forced convection indirect solar dryers. Solar Energy. 2022;234:319-29.