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Research Article

Performance Evaluation of a Solar Dryer with Flat Plate Collector for Efficient Grape Dehydration

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Abstract *- This study investigates the effectiveness of a solar dryer utilizing an FPC system for the dehydration of grapes. The study aims to assess the efficiency of the dryer under different environmental conditions. A flat plate collector, measuring 2 meters in length and 0.8 meters in width, was chosen to capture solar energy. This heated air is directed through an insulated drying chamber containing three mesh trays with stainless steel material. Experimental results demonstrated a substantial temperature rise within the dryer, reaching up to 80°C, driven by effective solar radiation capture. Solar radiation and relative humidity measurements revealed a significant correlation between midday solar peaks and optimal drying conditions. Moisture removal followed a rapid initial phase, transitioning to a slower, steady phase, with drying rates aligning with standard solar drying behaviors. The overall efficiency peaked during midday, underscoring the dryer's capability to maintain effective drying environments. This study validates the solar dryer's design, demonstrating its potential for efficient, sustainable dehydration of agricultural products. Future work should focus on optimizing dryer design and material selection to further enhance performance and efficiency*.

Keywords ***-*** *Solar dryer, Flat plate collector, Grape dehydration, Thermal efficiency, Moisture removal rate.*

1. Introduction

In recent years, there has been a growing global concern about adopting sustainable practices across various sectors, including agriculture. With agriculture being a cornerstone of economies worldwide, the need for efficient and eco-friendly methods of crop processing and preservation has become paramount. In this context, solar drying has emerged as a promising solution, offering a sustainable and cost-effective means of preserving agricultural produce while minimizing energy consumption and environmental impact. Solar drying harnesses the abundant energy of the sun to remove moisture from agricultural products, thereby extending their shelf life and reducing post-harvest losses. Among the various solar drying technologies, passive flat plate collector solar dryers have garnered significant attention due to their simplicity, low cost, and ease of operation. These dryers utilize a combination of solar radiation, natural convection, and thermal insulation to create a conducive environment for drying agricultural commodities. The potential advantages of passive flat plate collector solar dryers in agricultural applications are significant, but their design and performance assessment must carefully account for factors such as climate conditions, the properties of the products being dried, and the dynamics of the drying process. Furthermore, optimizing the design parameters such as collector area, insulation thickness, and airflow patterns is essential to maximize drying efficiency and minimize drying time.

Several researchers have investigated the design parameters affecting the performance of passive flat plate collector solar dryers. In their study, Tian Chang [1] emphasized the importance of collector area, orientation, and tilt angle in maximizing solar radiation absorption and heat transfer efficiency. Similarly, Benallel et al. [2] highlighted the significance of insulation thickness and material selection in minimizing heat losses and improving dryer performance. Furthermore, research efforts have focused on enhancing the drying kinetics and efficiency of solar dryers through innovative design features. For instance, Ebrahimi et al. [3] proposed the combination of PCMs into the dryer structure to enhance thermal storage capacity and prolong drying periods, particularly during nighttime or cloudy conditions. Similarly, Elgendi et al. [4] investigated the use of transparent insulation materials to enhance solar radiation absorption while minimizing heat losses, thereby improving dryer performance under varying climatic conditions. Beyond design optimization, various studies have assessed the working of passive FPC solar dryers for drying particular agricultural products. For example, Khalifa et al. [5] conducted experiments to assess the drying properties of vegetables and fruits in a solar dryer equipped with adjustable airflow control mechanisms. Their findings demonstrated significant improvements in drying rates and product quality compared to traditional open-air drying methods. Furthermore, advancements in materials science have enabled the development of novel solar collector designs with improved optical and thermal properties. For example, Gupta and Dixit [6, 7] examined the use of nanofluid solar collectors, demonstrating notable improvements in thermal conductivity and energy absorption over conventional fluids. These advancements have the potential to enhance the performance and efficiency of solar drying systems in agricultural contexts. A key study by Rizalman et al. [8] offers a thorough review of both passive and active solar drying systems, detailing their design principles, thermal performance, and applications in drying various agricultural products. They emphasized the importance of proper design considerations, such as collector tilt angle, air flow rate, and drying chamber insulation, to improve the overall efficiency of solar dryers. Another noteworthy contribution by Gilago et al. [9] examined the drying of different crops. Their experimental results demonstrated that solar dryers significantly reduced drying time. They also highlighted the impact of airflow rate intensity on the drying process.

In a study by Adelaja and Babatope [10], the authors developed and tested a passive solar dryer for drying fruits and vegetables. Their findings indicated that the dryer could achieve uniform drying with minimal energy consumption, making it suitable for farmers. They also discussed the potential for scaling up such systems to meet larger demands. Hin et al. [11] explored dryers for fish preservation, presenting a detailed analysis of the drying characteristics and quality of dried fish. Their research demonstrated that solar drying could effectively extend the shelf life of fish products, providing a viable alternative to traditional smoking and sun drying methods. Further, Tarigan [12] proposed a model (mathematical) to know the performance of a passive solar dryer under various climatic conditions, enabling accurate prediction of drying times and efficiency.

The model's validation with experimental data confirmed its reliability and applicability for designing solar dryers tailored to specific regions and crops. Additionally, Ahmad and Prakash et al. [13] evaluated a solar-assisted drying system integrated with a greenhouse. Their research highlighted the advantages of combining solar drying with greenhouse technology, including enhanced drying rates and protection from adverse weather conditions. This approach was particularly beneficial for high-value crops and regions with fluctuating weather patterns. Moreover, researchers have explored the integration of solar drying technology into broader agricultural value chains to promote sustainable development and enhance livelihoods. Ndukwu [14] examined the economic viability of solar drying systems for smallholder farmers in rural Bangladesh, highlighting the potential for income generation and food security enhancement through reduced post-harvest losses.

Despite these advancements, there remains a notable gap in understanding how specific design and operational parameters interact to influence the overall performance of solar dryers under varying environmental conditions. Previous studies have primarily focused on isolated aspects of solar dryer performance, such as airflow control [5], material innovations [7], and the integration with greenhouse technology [13]. However, there is limited comprehensive research that systematically investigates the combined effects of critical parameters—such as ambient temperature—on the drying process and thermal efficiency in a holistic manner.

The objectives of this research are to conduct an experimental investigation to assess the dryer's effectiveness under various climatic conditions and to investigate the influence of critical design and operational parameters, including airflow rate, solar radiation intensity, and ambient temperature, on drying performance and thermal efficiency.

2. Materials and Methods

2.1. Experimental Setup

Figure 1 illustrates the schematic arrangement of the solar dryer. Several experimental tests were conducted in April 2024 to assess solar collectors and the drying behavior of grapes. The grapes were dried in a specially fabricated and designed solar dryer. Each experiment processed a 10 kg batch of grapes sourced from the local market in Washim, India. The oven-dry method is used to measure the initial moisture content.

2.2. Solar Dryer Design and Fabrication

The solar dryer was designed following an extensive literature review, which guided the selection of a flat plate collector system for experimentation. Design parameters, such as the total exposed solar collector area and mass flow rate, were determined accordingly. The necessary area for the solar dryer was calculated to be 1.6 m², sufficient to dry 10 kg of grapes.

2.3. Design Specifications

FPC Consists of copper tubes, each aligned parallel to achieve the required exposed area. These tubes were connected to a central tube (60 mm diameter) at the top, which directs the hot air to the bottom of the dryer chamber. The FPC was inclined at 23 degrees to the horizontal on a steel frame to maximize the absorption of solar radiation. Dryer Chamber is constructed from 0.6 mm thick aluminum alloy sheets, with inlet and outlet sections at the bottom and top, respectively, to ensure uniform hot air flow. The chamber was insulated with a 50 mm polyethylene foam sheet to minimize heat loss. The drying chamber was equipped with three SS mesh trays to hold the grapes. For calculation, it was assumed that 10 kg of grapes, initially containing 80% moisture (on a wet basis), would be dried to a final moisture level of 15% (on a wet basis) over 40 hours.

The collector has an exposed area of 1.61 square meters for capturing solar radiation. The dimensions of the drying chamber are as follows: it measures 0.64 meters in height, 1.0 meters in length, and 0.64 meters in width. Each dryer tray has an area of 0.6 x 0.6 square meters. The dryer chamber contains three trays, with a vertical distance of 0.25 meters between each tray. The angles of convergence and divergence to the dryer are set at 15 degrees. These specifications ensure the optimal design and efficient operation of the solar drying system for agricultural products.

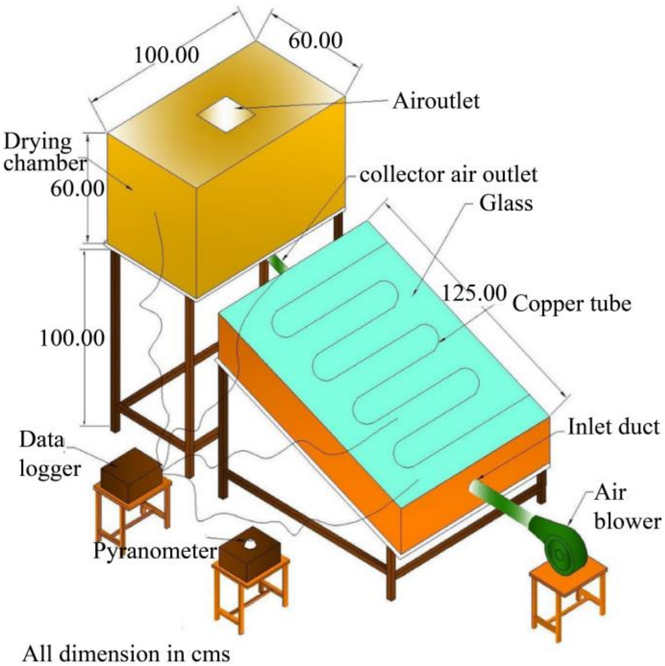


Fig. 1 Schematic arrangement of experimental setup

2.4. Equations Used in Analysis

The mass of water to be evaporated, which represents the mass of water removed from the grapes, is determined using Equation 1.[15].

$$m_w = \frac{m_p(m_i - m_f)}{100 - m_f} \quad (1)$$

Where, m_w is the mass of water to be evaporated, m_p is the total mass of grapes (kg) to be dried with initial moisture content m_i to Final Moisture Content m_f.

The heat required for evaporation calculates the total heat needed to evaporate the water content [16].

$$Q_{req} = \frac{M_w - L_w}{3600 * t} \quad (2)$$

The drying rate is defined as the amount of moisture removed per unit of time and is calculated using Equation 3 [17].

$$D_R = \frac{m_w}{\Delta T} \quad (3)$$

The total heat absorbed by the ETC (Evacuated Tube Collector) system is determined using Equation 4 [18].

$$Q_{abs} = A_C * I_G * \eta_{opt} W \quad (4)$$

Where, η_{opt} is the optional efficiency of the flat plate collector, which is 0.65 and I_G is solar radiation falling on the surface of the collector.

The discharge flow rate of hot air, which represents the flow rate of hot air passing through the system, is given by Equation 5 [19].

$$Q = \frac{V_{air}}{\Delta t} \quad (5)$$

Moisture Ratio (MR) is a non-dimensional parameter calculated to assess drying performance [20].

$$MR = \frac{(M_t - M_e)}{(M_i - M_e)} \quad (6)$$

Where, M_t is the mass of the product at any time 't', and M_e is equilibrium moisture.

The thermal efficiency of a flat plate collector is defined as the ratio of the heat gained by the working fluid to the product of the solar radiation incident on the collector surface and its exposed area. This efficiency is calculated using Equation 7 [21].

$$\eta_{coll} = \frac{Q_u}{A_c * I_G} * 100 \quad (7)$$

3. Results

3.1. Temperature Elevation in Solar Dryer

The results showed a marked increase in temperature inside the solar dryer, climbing from an initial 31°C to a maximum of 80°C. This significant temperature rise was mainly due to the efficient capture and retention of solar radiation by the flat plate collector. The difference in temperature between the ambient air and the drying air in the chamber created a notable temperature gradient, denoted as ΔT, which was adequate to drive the process of drying the grapes in the solar dryer. The observed ΔT was instrumental in achieving effective moisture removal from the grapes, underscoring the efficiency of the dryer in creating an optimal drying environment. The high internal temperatures accelerated the evaporation of moisture from the grape surfaces, thereby enhancing the drying rate. The ability to maintain such elevated temperatures consistently throughout the drying process is crucial for the dehydration of agricultural products, ensuring both efficiency and quality preservation.

3.2. Measurement of Solar Radiation and Relative Humidity

Figure 2 illustrates the solar radiation (W/m²) measured at hourly intervals from 9 am to 6 pm over four consecutive days. Each day's solar radiation data is represented by distinct coloured bars (blue for day 1, orange for day 2, gray for day 3, and yellow for day 4), while the red line with dots depicts the average solar radiation across these days. The observed pattern reveals a substantial increase in solar radiation starting from the morning, peaking around midday, and then gradually decreasing as the day progresses towards the evening.

On average, the solar radiation starts at approximately 400 W/m² at 9 am, peaks at around 1000 W/m² between 12 pm and 1 pm, and decreases to about 200 W/m² by 6 pm. This bell-shaped curve indicates that the solar intensity occurs at midday, creating optimal conditions for solar energy applications. The day-to-day variations in solar radiation values suggest differences in atmospheric conditions, such as cloud cover, which can impact the efficiency of solar dryers. Overall, the graph highlights the potential for harnessing solar energy, particularly during peak radiation periods, which is crucial for the effective operation of solar dryers.

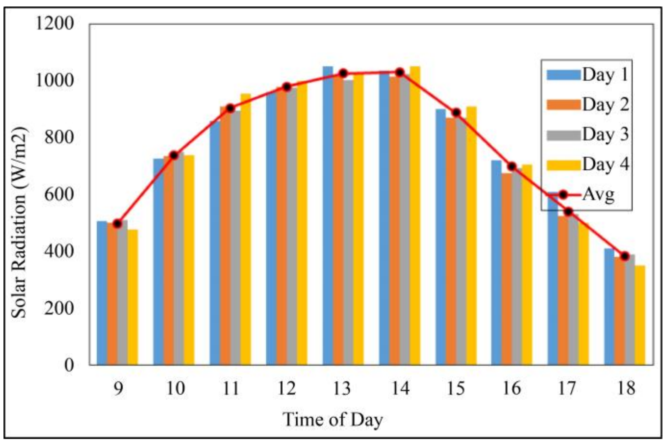


Fig. 2 Variation of solar radiation

Figure 3 depicts the relative humidity (%) measured at hourly intervals from 9 am to 6 pm over four consecutive days. The observed trend indicates a general decrease in relative humidity from the morning through the early afternoon, followed by a significant increase towards the evening. Initially, the relative humidity starts high, averaging around 25-30% at 9 am, and then decreases steadily, reaching its lowest point of approximately 15-20% between 12 pm and 2 pm. This decrease correlates with the period of peak solar radiation, where increased temperatures result in lower relative humidity. As the day progresses towards the late afternoon and evening, relative humidity increases sharply, peaking again at around 35-40% by 6 pm. This pattern suggests that solar radiation decreases, resulting in higher relative humidity levels. The variations in relative humidity between the days highlight the influence of daily atmospheric conditions, including temperature fluctuations and solar radiation intensity. This diurnal humidity pattern is critical for solar drying applications, as lower relative humidity during peak sunlight hours enhances the drying process by facilitating more efficient moisture removal from agricultural products. Understanding these humidity trends is crucial for optimizing the operation and design of solar dryers, ensuring they deliver effective and consistent drying performance.

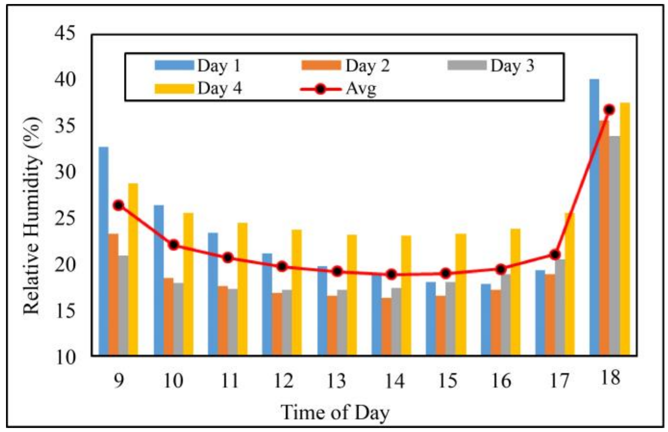


Fig. 3 Variation of relative humidity

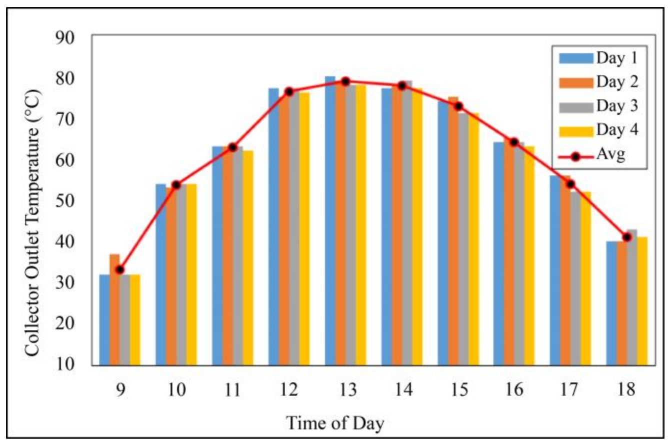


Fig. 4 Variation of collector outlet temperature

3.3. Collector Outlet Temperature

Figure 4 presents the collector outlet temperature (°C) recorded at hourly intervals from 9 am to 6 pm over four consecutive days. The data reveals a clear diurnal pattern in the temperature variations, which aligns with the typical solar radiation cycle. The collector outlet temperature starts at approximately 30-40°C at 9 am and rises consistently throughout the morning, peaking between 12 pm and 1 pm at around 80-85°C. This midday peak corresponds to the period of maximum solar radiation, where the solar collector effectively captures and converts solar energy into thermal energy. After midday, temperatures gradually decrease, falling to around 40-50°C by 6 pm as solar intensity diminishes and ambient temperatures cool. The average temperature trend line shows a bell-shaped curve, peaking at midday, which is indicative of the optimal operational period for the solar dryer. The consistent peak temperatures across all four days suggest a reliable performance of the solar collector under various atmospheric conditions. These elevated temperatures at the collector outlet are crucial for efficient drying processes, as they facilitate rapid moisture removal from agricultural products. Analyzing the fluctuations and peaks in the collector outlet temperature is vital for optimization. The data suggests that the solar dryer can sustain adequately high temperatures during peak sunlight hours, thereby ensuring efficient and effective drying of the produce.

3.4. Mass of Grapes

Figure 5 illustrates the variation in the mass of grapes (in kilograms) throughout different times of the day over a period of four days. The trends demonstrate a general decline in the mass of grapes as the day progresses. Day 1 starts with the highest mass, peaking at approximately 10.5 kg at 8 am, and steadily decreases to about 7.5 kg by 6 pm. Similarly, Day 2 shows a decrease from around 8 kg to 5.5 kg, Day 3 from 6.5 kg to 4.5 kg, and Day 4 from 4.5 kg to 3 kg. The average mass (marked in red) follows a similar pattern, indicating a consistent reduction in grape mass throughout the day. This suggests a possible diurnal variation in the mass of grapes, potentially due to factors such as water loss or consumption.

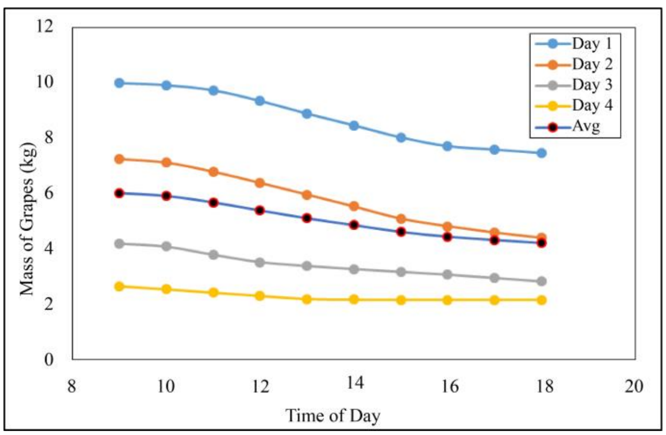


Fig. 5 Variation of mass of grapes

3.5. Heat Gain by the Grapes

Figure 6 illustrates the diurnal variation in heat gain (measured in joules per second, J/s) by air using a flat plate collector solar dryer over four days. The results indicate a consistent pattern of heat gain throughout the day, characterized by an initial low level in the early morning, a peak around midday, and a subsequent decline in the late afternoon. Specifically, heat gain starts at approximately 50 J/s at 9 am, increases sharply, and reaches a maximum of around 450 J/s between 12 pm and 2 pm, before decreasing to approximately 100 J/s by 6 pm.

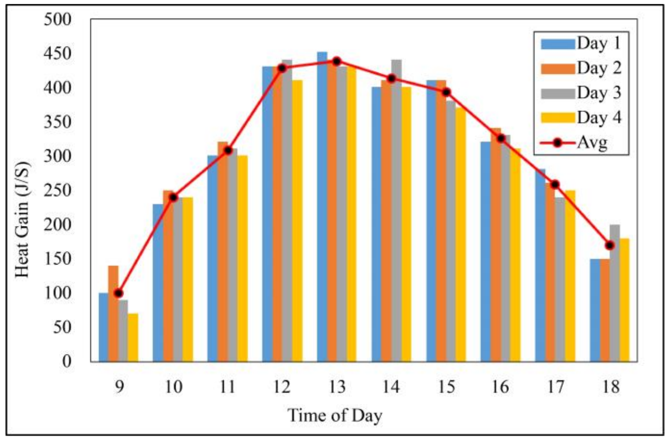


Fig. 6 Variation of heat gain by the air

These findings are consistent with the typical performance of flat plate collector solar dryers, where solar radiation is captured and converted into heat energy, leading to increased temperatures within the drying chamber during the peak solar hours [22]. The observed peak in heat gain at midday aligns with the highest solar irradiance. The subsequent decline in the afternoon is attributed to reduced solar input and the effects of radiative and convective cooling [23]. The average heat gain profile suggests that the flat plate collector solar dryer operates efficiently, providing substantial heat energy during critical drying hours, which is essential for effective grape dehydration. This diurnal heat gain pattern is crucial for optimizing the drying process, ensuring that the grapes lose moisture consistently and evenly throughout the day [24].

3.6. Thermal Efficiency

Figure 7 illustrates the thermal efficiency of an FPC solar dryer over a four-day. The thermal efficiency shows a marked increase from early morning to late afternoon. Starting from about 5% at 9 am, the efficiency rises sharply to reach around 20-30% by 11 am. The efficiency stabilizes somewhat between 12 pm and 3 pm, maintaining levels between 25% and 35%. Notably, there is a significant increase observed from 4 pm onwards, with the efficiency peaking at approximately 45-50% by 6 pm. These results align with the typical thermal performance characteristics of FPC, where efficiency is affected by factors such as solar radiation intensity [25]. The initial low efficiency in the morning is due to lower solar irradiance and higher heat losses. As solar radiation intensifies towards midday, the collector's efficiency improves, reaching a plateau when the balance between heat gain and losses is relatively stable [26] [27].

Furthermore, the solar dryer's effective design and materials likely help it sustain higher efficiency levels even as solar irradiance wanes in the evening. These efficiency trends indicate that the flat plate collector solar dryer performs optimally during the crucial midday to late afternoon period, which is essential for maximizing the drying rate and overall performance of the drying process [28].

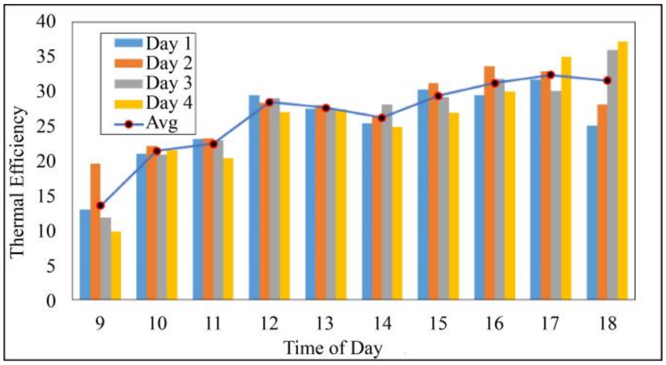


Fig. 7 Variation of thermal efficiency

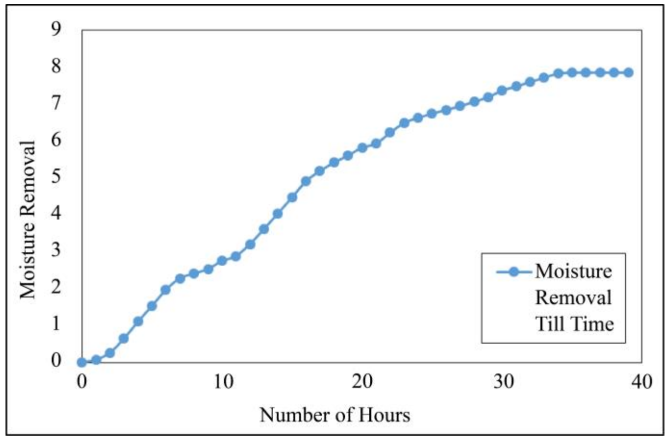
3.7. Moisture Removal Rate Over Time

Figure 8a illustrates the cumulative moisture removal from grapes over 40 hours in a solar dryer. Initially, there is a rapid increase in moisture removal within the first 10 hours, reaching approximately 3 units of moisture removed. This phase is likely due to the grapes' high moisture content, which accelerates the evaporation rate during solar drying. From hours 10 to 20, the rate of moisture removal appears to slow down, with the total moisture removal increasing from 3 to about 5 units.

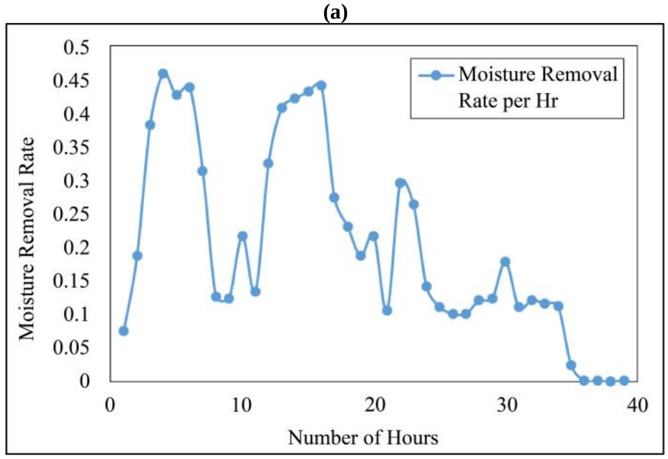
This intermediate phase likely indicates a reduction in the surface moisture, leading to slower moisture migration from the inner tissues of the grapes to the surface. Beyond the 20-hour mark, the rate of moisture removal continues at a relatively steady, albeit slower, rate. The moisture removal increases gradually from 5 to approximately 8 units by the end of the 40-hour drying period. This plateau phase suggests that the remaining moisture is more tightly bound within the grape tissues, requiring more time and consistent exposure to solar heat to be effectively removed.

Figure 8b shows the hourly moisture removal rate, providing a more detailed insight into the drying dynamics. The moisture removal rate peaks multiple times, with the highest rates observed at around 5 and 15 hours, reaching up to 0.45 units per hour. These peaks correspond to periods of intense solar exposure and optimal drying conditions. Between these peaks, the moisture removal rate drops significantly, approaching zero around the 10th and 20th hours. These declines can be attributed to fluctuations in solar intensity, changes in ambient conditions, or the shifting phases of drying (surface vs. internal moisture). After the 20-hour mark, the moisture removal rate demonstrates smaller peaks and valleys, with the overall rate decreasing towards the end of the drying period. This consistent decline reflects the increasing difficulty in removing the remaining moisture from the grapes, which are more deeply embedded and less responsive to solar drying.

The observed drying pattern is consistent with findings from previous studies on solar drying of agricultural products. According to Gomez et al. [29], the drying process typically exhibits an initial rapid phase followed by a slower rate of moisture removal, similar to the trends observed in this study. Additionally, the presence of multiple peaks in the drying rate graph aligns with the findings of Seveda et al. [30], who noted that variations in solar intensity and ambient conditions can lead to fluctuating drying rates.



(a)



(b)

Fig. 8 Moisture removal (a) Till time, (b) Rate per hour

3.8. Drying Rate Per Hour

Figure 9 illustrates the drying rate per hour of grapes using a solar dryer over a total duration of 40 hours. Initially, there is a rapid increase in the drying rate within the first 5 hours, reaching a peak of approximately 0.14 kg/hour around the 4th hour. This peak signifies the maximum drying rate achieved during the entire drying process. Following this peak, the drying rate exhibits a steep decline, dropping to about 0.03 kg/hour by the 8th hour. From the 9th hour onwards, the drying rate shows a more gradual decrease with intermittent minor fluctuations. Between the 10th and 20th hours, the drying rate stabilizes somewhat, around 0.02 kg/hour. After the 20th hour, the drying rate continues to decline slowly, approaching near zero by the 40th hour.

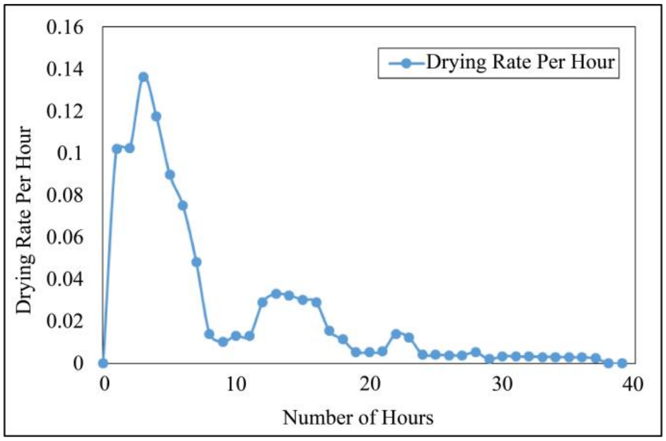


Fig. 9 Drying rate per hour

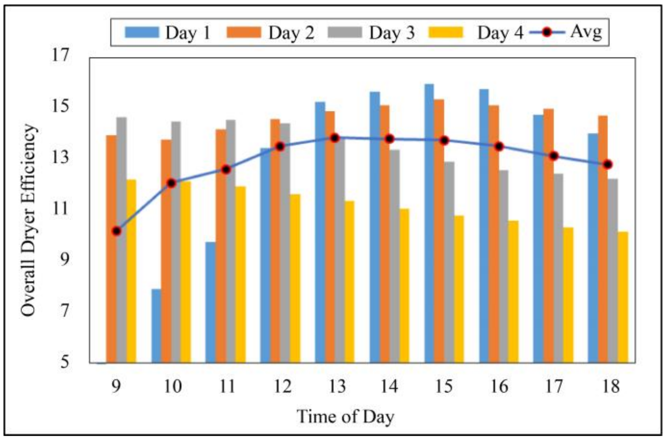


Fig. 10 Overall dryer efficiency

Overall, the drying rate per hour demonstrates a characteristic pattern of an initial rapid increase to a peak value, followed by a sharp decline and eventual stabilization at a lower rate. This behavior is typical in drying processes where the initial moisture content is high, leading to a high drying rate that gradually decreases as the material becomes less moist.

3.9. Overall Dryer Efficiency

Figure 10 illustrates the overall efficiency of the solar dryer for grapes over four days, measured at different times throughout the day. At 9 am, the overall dryer efficiency starts relatively low, with Day 1 at approximately 10% and Days 2, 3, and 4 varying between 11% and 15%. The average efficiency at this time is around 12%. As the day progresses, the overall efficiency increases, peaking between 12 pm and 2 pm. During this period, the average efficiency stabilizes around 15%, with Day 1 showing a significant increase to 16% by 12 pm and Days 2 and 3 maintaining efficiencies around 14% to 16%. In the afternoon, from 2 pm to 4 pm, the overall efficiency shows a slight decline. The average efficiency remains consistent at approximately 15%, though individual days demonstrate slight variations. Day 4 generally exhibits lower efficiencies compared to other days during these hours.

By late afternoon and early evening, from 4 pm to 6 pm, the overall efficiency begins to decline more noticeably. The average efficiency decreases to about 14% by 6 pm, with individual days ranging between 12% and 16%.

Overall, the graph indicates that the solar dryer's efficiency tends to peak around midday and gradually declines towards the evening. The average efficiency line provides a clear indication of this trend, showing a relatively high performance during the middle of the day and lower efficiency during the early morning and late afternoon.

4. Conclusion

This research article provides a thorough assessment of a solar ETC system for drying Thompson seedless grapes. The study includes the evaluation of dryers under different environmental conditions.

- The solar dryer demonstrated an increase in internal temperature, with a peak of 80°C achieved, facilitating effective moisture removal. The average temperature profile and thermal efficiency were consistent with optimal drying conditions, peaking around midday. The observed high temperatures and efficiency underscore the dryer's capability to maintain an effective drying environment.
- The drying process exhibited a rapid initial moisture removal phase, followed by a slower, steady phase. The observed drying rates and moisture removal patterns align with typical solar drying behaviors, indicating effective moisture evaporation and consistent drying performance.
- The heat gain by the air and the corresponding mass loss of grapes were closely monitored, revealing a clear correlation between solar radiation intensity and drying efficiency. The data confirmed that the solar dryer effectively transferred solar energy into thermal energy, enhancing the drying process.
- The solar dryer achieved its highest overall efficiency at midday, with a decline in efficiency as the day progressed towards the evening. This efficiency pattern is consistent with the variations in solar radiation and ambient conditions, suggesting that the solar dryer operates optimally during peak sunlight hours.

In conclusion, the designed solar dryer with an ETC system effectively harnesses solar energy to dry Thompson seedless grapes, achieving substantial temperature elevation, efficient moisture removal, and consistent drying rates. The study demonstrates the viability of using solar drying technology for agricultural products, offering a sustainable and efficient method for dehydration. Future research could explore further optimization of the dryer design, including enhancements in material selection and structural configurations, to improve overall efficiency and performance.

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