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Original Article

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Design and optimization of an active and passive mode indirect solar dryer to improve energy efficiency and sustainability

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Abstract

This paper compares the behavior of active (forced convection) and passive (natural convection) indirect solar dryers when it comes to drying green chilies, in terms of thermal behavior, drying kinetics and retentiveness of products. Similar climatic conditions were done so as to compare the rate of moisture removal, thermal efficiency as well as specific moisture extraction rate (SMER). The active dryer reached a high temperature in the drying chamber of 65°C and decreased moisture content of 85% to 10% (wb) in 6 h under similar input measures as compared to the passive dryer, which took 12 h with similar input measures. The active dryer registered SMER and thermal efficiency values of 0.75 kg/kWh and 55%, respectively, compared to 0.45 kg/kWh and 35% of the passive dryer. The quality analysis revealed that the active dryer was much better in terms of color retention and flavor stability because of reduced exposure time and higher heat transfer. In a nutshell, the active system decreased active time by 40% and energy used per unit product, thus showing that it would be appropriate in decentralized agricultural processing with the use of solar energy.

Keywords solar drying, green chilies, affordable and clean energy, passive mode, indirect solar dryer, thermal efficiency

Nomenclature

Symbol	Description	Unit
Roman symbols		
A	Area of solar dryer	m^2
Cp	Specific heat capacity	$J\cdot kg^{-1}\cdot K^{-1}$
D	Amount of dried chilies	kg
Dr	Drying rate	$kg\cdot h^{-1}$
E	Energy	kJ
EE	Energy efficiency	%
hfg	Latent heat of vaporization	$kJ\cdot kg^{-1}$
I	Solar irradiance	$W\cdot m^{-2}$
MFR	Mass flow rate of air	$kg\cdot s^{-1}$
MRR	Moisture removal rate	$kg\cdot h^{-1}$
Mw	Mass of water evaporated	kg
m	Mass flow rate	$kg\cdot s^{-1}$
R	Solar radiation	$W\cdot m^{-2}$
t	Drying time	h
T	Temperature	°C/K
Ta	Ambient temperature	K
To	Outlet temperature	K
Wo	Initial mass of product	kg
Wf	Final mass of product	kg

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Greek symbols		
ηc	Collector efficiency	%
ηs	Storage efficiency	%
ηt	Thermal efficiency	%
χ^2	Chi-square parameter	–
Subscripts		
c	Collector	
f	Final	
i	Initial	
s	Storage	
t	Thermal	
Abbreviations		
ASD	Active solar dryer	
PSD	Passive solar dryer	
SAC	Solar air collector	
FC	Forced convection	
NC	Natural convection	
MC	Moisture content	
MFR	Mass flow rate	
MRR	Moisture removal rate	
SMER	Specific moisture extraction rate	
SEC	Specific energy consumption	
ANOVA	Analysis of variance	
ROI	Return on investment	
GHG	Greenhouse gas emissions	
SPSS	Statistical Package for the Social Sciences	

1. Introduction

Due to their use, there is growing interest in renewable energy technologies that are associated with sustainable agricultural practices, especially for food preservation. One such type of technology is solar drying, which uses solar energy to reduce moisture content (MC) in agricultural products, increasing their shelf life and their market value. A good example of a highly perishable product that has a high MC and thus will spoil soon is green chilies, which happen to be a widely used ingredient in many cuisines. Fossil fuels or climate dependence currently make most traditional drying methods subject to inconsistent quality and increased postharvest loss [1]. Hence, there is an urgent need for effective and sustainable drying solutions that can be used by farmers where there normally is plenty of sunlight available, and many studies have been performed on solar drying technologies for several crops and drying systems [2]. The process of solar drying compared to sun drying techniques increased tomatoes' drying rate by 50%, and the dryer also improved the retention of quality. Another study showed that indirect solar dryers could significantly shorten the drying time of fruits and vegetables, leaving their quality intact [3]. According to their analysis, their average MC reduction is around 70% for fruits dried by indirect solar dryers as compared to around 40% in traditional ones. Statistical analyses of previous studies on solar dryer performance have shown very significant differences, depending on their designs and operational parameters [4]. For instance, a comparative study concluded that active solar dryers (ASDs) can achieve thermal efficiencies of up to 70%, which is considerably higher than those of passive systems, typically ranging from 30% to 40% [5].

The existence of this disparity shows the importance of forced convection (FC) in increasing transfer rates of heat and moisture. Also, products dried in active systems maintained desirable quality attributes, such as color and flavor, at a much higher rate: color degradation occurring at 15% compared with 30% in passive systems [6]. Also, although there are multiple studies endorsing use of solar technologies for drying of agricultural products, limited research has been conducted to quantify the effects of various drying modes on product quality attributes: color, flavor, and nutritional content [7]. As an example, previous research pointed out that color retention is very important for the acceptance by consumers of dried products, but it did not show in detail comparative analysis of different modes of drying for particular crops [8]. According to their findings, products dried using active systems retained 85% of their original color, whereas products dried passively retained only 70% of their original color. In other words, products dried in indirect solar dryers experienced markedly lower ascorbic acid losses during drying compared to traditional sun drying methods [9]. They found that sun-dried samples lost approximately 50% of their initial ascorbic acid content, whereas samples dried using indirect solar dryers retained about 80% of their ascorbic acid content. Green chili drying processes are extensively discussed through statistical discussions, revealing specific performance metrics from such processes and thereby underscoring the potential of solar dryers in terms of not only improving efficiency of the process but also preserving nutritional value in agricultural products [10]. By 8 h, the sun dryer reduced green chili initial MC of 4.0 g water/g dry matter to 0.45 g water/g dry matter. However, over the same drying period, open sun drying resulted in a final moisture content (MC) of 1.15 g water/g dry matter. The results also reveal that the solar dryers removed moisture far more quickly, at a rate about 130% greater than natural open sun drying methods [11].

A statistical analysis was also conducted to determine which model was most suitable for predicting moisture ratios during solar drying, finding that the modified Henderson and Pabis model performed best with an R^2 value of 0.999 and minimal values for chi-square ($\chi^2 = 0.23 \times 10^{-4}$) and root mean square error [12]. These results confirm the reliability of the model in describing moisture drying dynamics. However, despite its many advantages, limited studies have evaluated the performance of active and indirect passive solar dryers (PSDs) under the drying conditions required for crops such as green chilies [13]. Current literature rarely offers detailed statistical comparisons of these two modes against each other, or under like environmental conditions and for specific produce type. For instance, some studies have investigated the thermal performance of several dryer designs without consistently measuring specific moisture extraction rate or energy consumption metrics between different dryer configurations, leaving gaps in the literature [14, 15]. Various previous studies have considered the hybrid solar dryers, but most of them are limited to one mode systems, one crop drying systems, or a research only on the kinetic phenomena, thus failing to integrate multilogic evaluation. Conversely, the current study provides a two-mode comparative study of the active and passive functioning, regarding dehydration of green chili under strictly controlled, the same climatic conditions. The performance is determined in relation to drying kinetics, thermal efficiency, moisture removal properties, and qualitative product properties under the same climatic conditions. Through this comparison, the impact of airflow mode [FC and natural convection (NC)] on the drying performance of green chilies in indirect solar dryers is explained. Even up to the present, no research has been able to combine simultaneously thermal, quality, sustainability, and economic performance indicators of a hybrid solar dryer system that incorporates FC as well as auxiliary heating to the process of dehydration of this specific crop. As a result, the holistic approach of methodology is the main scientific value of the given work and fills the major gap in research in the field of sustainability-focused decision-making in the sphere of solar drying.

Aiming to fill these gaps in the literature, this research carries out a systematic experimental study and analysis of active and passive mode indirect solar driers dedicated to dry green chilies. The aim of this study is to systematically compare performance metrics, including drying rate, thermal efficiency, moisture removal rates, and product quality, in order to help make informed decisions on how solar drying technologies, for this important crop, may be optimized. The goal is to examine how varied modes of operation influence not only the performance of moisture removal, but also the retention of key quality attributes in green chilies dried by solar means. An empirical basis of knowledge will be generated for farmers to be able to choose appropriate solar drying technologies from the growing body of knowledge on sustainable agricultural practices [16]. Another purpose is to fill in the knowledge gap on comparing the relative effectiveness of active vs passive indirect solar dryers for green chilies, so that better food preservation methods that are environmentally friendly and economically viable are promoted [17]. Wide adoption of solar drying technologies by small-scale farmers in areas where green chilies constitute an important agricultural commodity will also result from addressing these objectives through thorough statistical analysis, including analysis of variance (ANOVA) tests for comparing moisture removal rates between dryer types and regression analysis to correlate temperature profiles with product quality. Statistical methodologies will be incorporated such that findings are robust and applicable in different contexts, and lay the grounds for future research into optimizing solar drying systems to other crops in addition to green chilies.

2. Experimental setup and procedure

For this research, the experimental setup was designed for examining performance of active and passive mode indirect solar dryers tailored to dry green chilies. This study was pursued to compare the efficiency, drying rate, and quality retention of the dried product in both systems. The experimental apparatus consisted of two distinct configurations: an FC ASD and a PSD based on NC as shown in Fig. 1. The performance is determined in relation to drying kinetics, thermal efficiency, moisture removal properties, and qualitative product properties under the same climatic conditions. Through this comparison, the impact of airflow mode (FC and NC) on the drying performance of green chilies in indirect solar dryers is explained. The flat plate design collector was 23.5 cm thick, 190 cm long, and 122.5 cm wide. Corrugated galvanized iron forming the base plate surface was matte black, having a thickness of 0.2 cm. A 0.4-cm-thick roof of transparent glass was placed over the collector in order to create a greenhouse effect in which the heat would be trapped in the collector. A layer of 4-cm-thick

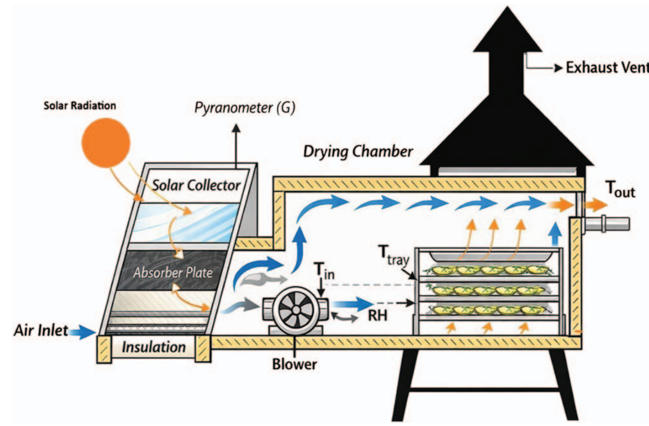

Figure 1 Experimental setup.

polystyrene was used for rear insulation of the system to minimize heat loss during operation, while the PSD was designed to be similar in design but without fans for mechanicals. It was dependent on NC to circulate air in the drying chamber. The chamber was 50 cm wide, 60 cm high, 100 cm long, divided into four trays made of food-grade mesh so chilies could have the best possible airflow around them. To enable effective air to produce heat transfer, each tray was separated by 20 cm. In order to monitor key parameters throughout the drying process, various instruments were used (Table 1). Temperatures were measured at different points within both dryers using LCD digital thermometers, at the inlet and outlet of the solar air collector (SAC), and at different locations within the drying chamber. The accuracy of these thermometers is ±0.1°C. Air velocity in the system was measured by an anemometer (Model LIN 32967), with a range of 0–30 m/s and accuracy of 5%. A pyranometer was also used to determine the solar radiation level with an error of ±5 W/m^2 in Table 2. It is recorded that no auxiliary electrical heating component was incorporated in the system, and that the only electrical energy consumption could be attributed to the blower used in forced drying in the active dryer. Drying experiments were done in the summer months of May–June 2025 in the Mechatronics Engineering Department of the Hindusthan College of Engineering and Technology, Coimbatore, India (11.02°N, 76.96°E). The dry trials were carried out three times ($n = 3$) to provide the necessary reproducibility and statistics analysis; both active and passive operation modes were performed in each of the three cases, and the mean values were used to examine the performance.

Firstly, green chilies were harvested freshly from local farms, sorted by size and quality, all under fresh conditions to ensure uniformity in drying conditions [18]. To use as baseline data for future analysis, the initial MC was measured with a moisture analyzer. The chilies were spread out evenly on the drying trays in both dryers, and operation began in the morning when sunlight intensity became elevated. Parallel to the passive dryer, the powered-on ASD was used to create FC in the drying chamber [19]. Temperature and humidity were continuously recorded at various intervals during the drying process using data loggers connected to thermocouples and hygrometers strategically placed in both systems, throughout the drying process until the green chilies achieved an MC of approximately 10%, commonly accepted as the optimal moisture level of green chilies for long-term storage without spoiling. The same moisture analyzer that

Table 1 Major components of the experimental setup

Component	Specification/description	Range/values
SAC	Flat plate collector with an absorber to heat air	Dimensions: 190 × 122.5 × 23.5 cm
Absorber plate material	Galvanized iron with a matte black finish	Thickness: 0.2 cm
Glass cover	Transparent cover for greenhouse effect	Thickness: 0.4 cm
Drying chamber dimensions	Chamber for drying produce	Dimensions: 50 × 60 × 100 cm
Tray material	Food-grade mesh for air circulation	Separation: 20 cm between trays
Thermocouples	Used for temperature measurement	Accuracy: Â ± 0.1 Â °C
Anemometer	Measures air velocity	Range: 0–30 m/s, accuracy: Â ± 5%
Pyranometer	Measures solar radiation levels	Accuracy: Â ± 5 W/mÂ^2
Moisture analyzer	Determines MC	Initial MC: ∼85% wet basis, target final moisture: ∼10% wet basis
Data logger	Records temperature and humidity data	Continuous monitoring capability
Fan (active dryer)	Provides FC airflow	Voltage: 12 V

Table 2 Measuring instruments used and their specifications

Instrument	Measured parameter	Range	Accuracy/resolution
Thermocouples	Temperature	−50°C to 200°C	±0.1°C
Anemometer (LIN 32967)	Air velocity	0–30 m/s	±5%
Pyranometer	Solar irradiance	0–2000 W/m^2	±5 W/m^2
Moisture analyzer	MC	0%–100% (wb)	±0.001 g
Digital hygrometer	Relative humidity	0%–100% RH	±3%
Data logger	Temperature and RH logging	Continuous	1-min sampling interval
Colorimeter	Color index (CIELAB)	L∗, a∗, b∗ scale	Δ*E* resolution 0.01
Balance (BMA150)	Sample mass	0–200 g	±1 mg
Balance (BPS40plus)	Sample mass	0–40 kg	±1 g

was used at the start of the experiment determined the final MC [20]. Measurements of weight and MC were taken from samples from both dryers at predetermined time intervals every hour for the first 4 h and every 2 h thereafter (to monitor changes that occur during drying). Postdrying evaluations consisted of sensory panels to assess color retention and flavor quality. The collected data were then analyzed using statistical methods such as Statistical Package for the Social Sciences (SPSS) or R to statistically assess the significant differences in performance metrics between the two types of dryers. A colorimeter quantified the resulting changes in hue or brightness that resulted from different drying methods, and nutritional analysis varied from key vitamins such as ascorbic acid (vitamin C) content. ANOVA tests are conducted on triplicate measurements ($n = 3$) to compare means between different parameters including moisture removal rate, thermal efficiency, color retention percentage, and nutritional performance. ANOVA was used to determine the presence and statistically significant difference in the mean values of the performance measures (drying rate, moisture reduction, and thermal efficiency) between active and passive operational regimes. The method is very appropriate in comparison to various groups or treatments and in determining whether observed differences are due to operational modality and not due to stochastic variability. The correlation and regression analyses were used to measure the relationship between temperature profiles, ratio of moisture, and drying time and measure the extent to which these variables are associated. This type of parametric modeling is necessary to understand the operation of drying, forecast behavior of moisture, as well as compare forced vs natural modes of convection. The following formulas are used to find out various results related to this research.

1. Weight of water evaporated

$$M_w = W_o - W_f \tag{1}$$

where M_w = weight of water evaporated (kg), W_o = initial mass of product (kg), W_f = final mass of product (kg)

2. Drying rate

$$D_r = \frac{M_w}{t} \tag{2}$$

where D_r = drying rate (kg/h), M_w = weight of water evaporated (kg), t = drying time (h)

3. Thermal efficiency of the dryer

$$\eta_t = \frac{M_w * h_{fg}}{A_c * I} \tag{3}$$

where η_t = thermal efficiency (%), M_w= total mass of water evaporated from the drying product (kg), h_{fg} = latent heat of vaporization of water (kJ/kg), A_c = area of solar dryer (m^2), I = solar irradiation (w/m^2). The latent heat of vaporization (h_{fg}) in this work was calculated as a relationship of drying air temperature with the formula h_{fg} = 2501–2.326Td (T in °C), according to the ASHRAE psychometrical equation. The values of h_{fg} obtained within the range of drying temperatures between 60°C and 65°C are between 2350 and 2360 kJ/kg.

4. Collector efficiency

$$\eta_c = \frac{E}{A_c * I} \tag{4}$$

where η_c = collector efficiency (%), E = total useful energy received by the drying air (kJ), A_c = area of the solar collector (m^2), I = total global radiation on the horizontal surface during the drying period (kJ/m^2).

5. Storage efficiency

$$\eta_s = \frac{E_{\text{stored}}}{E_{\text{input}}} \tag{5}$$

where η_s = storage efficiency (%), E_{stored} = energy stored in the thermal energy storage materials (kJ), E_{input} = total energy input into the system (kJ)

6. Amount of sensible heat energy storage

$$E = M_a * C_p * (T_f - T_i) \tag{6}$$

where E = energy storage (J), M_a = weight of storage materials (kg), C_p = specific heat capacity of storage material (J/kg °C), T_f = initial temperature of the storage materials (°C), T_i = final temperature of the storage materials (°C).

The blower subsystem used 40 W of electrical power when operating in the case of the active dryer. Considering that the drying period was about 6 h, the total amount of electricity per single drying cycle waste was $E_{\text{elec}} = 40\ \text{W} \times 6\ \text{h} = 0.24\ \text{kWh}$. This is an electrical element included in the specific energy consumption (SEC) methodology to make sure that the total energy expenditure is sufficient to reflect the input of the solar thermal energy as well as the input of electrical energy in the form of auxiliary. To assess the quality of thermal energy, a streamlined exergy analysis was done using the following:

$$EX = \dot{m}_a C_{pa} (T_o - T_a) \left(1 - \frac{T_a}{T_o}\right) \tag{7}$$

where T_a and T_o refer to the ambient and outlet air temperatures (K), C_{pa} is the specific heat of air, and $\dot{m}_a$ is the mass flow rate. Exergy efficiency was defined as follows:

$$\eta_{ex} = \frac{EX_{\text{useful}}}{E_{\text{elec}} + E_{\text{solar}}} \tag{8}$$

The exergy analysis shows that despite the fact that the active dryer will need additional electrical energy, the increase in the useful exergy transfer and a significant reduction in drying time will improve the overall system performance. This in turn explains the fact that ASD is observed to have lower SEC per kilogram of dry product although its instantaneous energy consumption is higher.

2.1. Uncertainty and error analysis

Measurements that are experimental are always associated with uncertainties due to a measure of limitations in instrument accuracy, calibration, and work conditions. The uncertainties in this study included the temperature, relative humidity, air velocity, solar irradiance, and mass measurements because they affect the resultant drying performance measurements like the drying rate and thermal efficiency. The instrumental uncertainties were determined to the degree of accuracy specified by the manufacturers as given in Table 2. Equation (2) was used to calculate the drying rate (DR) by the following relation, DR = Mw/t, and the uncertainty that accompanies this was measured on the basis of standard root-sum-square (RSS). To propagate the uncertainty in a general parameter R as a function of independent variables x_i, the propagated uncertainty, δR is evaluated as follows:

$$\delta R = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial R}{\partial x_i} \delta x_i\right)^2} \tag{9}$$

The propagated uncertainty is stated as follows when it comes to the drying rate:

$$\delta \text{DR} = \text{DR}\sqrt{\left(\frac{\delta M_w}{M_w}\right)^2 + \left(\frac{\delta t}{t}\right)^2} \tag{10}$$

where δM_w and δt are the uncertainty terms of mass and time, respectively.

It was considered that the effect of the temporal uncertainty was insignificant due to the resolution of the digital balance and the constant sampling interval. In this regard, the thermal efficiency of the dryer as given in Equation (3) was developed as follows:

$$\eta_t = \frac{M_w h_{fg}}{A_c I} \tag{11}$$

With the help of the RSS formulation, the uncertainty of thermal efficiency was estimated as follows:

$$\delta \eta_t = \eta_t \sqrt{\left(\frac{\delta M_w}{M_w}\right)^2 + \left(\frac{\delta h_{fg}}{h_{fg}}\right)^2 + \left(\frac{\delta I}{I}\right)^2} \tag{12}$$

in which δh_{fg} is the uncertainty of the latent heat and $\delta I$is the uncertainty of the solar irradiance as is recorded by the pyranometer. Based on the given specifications in Table 2, the overall measurement uncertainties were calculated as being roughly ±0.3°C of temperature, ±5% of air velocity, ±5 w/m^2 of solar irradiance, ±2.1% of the drying rate, and ±3.4% of thermal efficiency. These uncertainties have been reflected in the performance parameters that have been reported and are seen in the error bars in the Results section. The uncertainty analysis thus inserted enhances the validity of the experimental results and enables the independent investigators to reproduce the results.

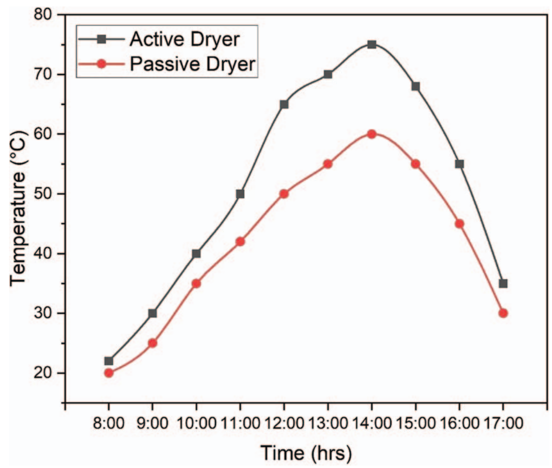

Figure 2 Temperature vs solar radiation.

3. Result and discussions

3.1. Temperature vs solar radiation

Results showed that in both dryer types, solar radiation and temperature were positively correlated. For example, the maximum temperatures achieved by the ASD were around 65°C, during peak sunlight hours, as opposed to approximately 50°C for the passive dryer during the same hours as shown in Fig. 2. The temperature difference was caused by the forced convection (FC) mechanism in the active dryer, which increased heat transfer and air circulation. The active dryer showed a Pearson correlation coefficient (r) of 0.92 and the passive dryer an r of 0.85, which are very strong correlations between solar radiation and temperature in both systems. To quantify this relationship further, regression analysis was performed. The regression equation for the active dryer was established as follows [21]:

$$T = 0.75R + 20 \tag{13}$$

The values reported are R, solar radiation in W/m^2, and T, temperature in °C. This equation states that the temperature, inside the active dryer, increases with 0.75°C for each 1 W/m^2 increase in solar radiation, and the baseline temperature is 20°C when there is no solar radiation. In comparison, the regression model for the passive dryer yielded the following [22]:

$$T = 0.55R + 18 \tag{14}$$

To validate these findings, an ANOVA test was performed to test whether variations in average temperatures between the two dryers, at increasing levels of solar radiation, indicated a statistically significant difference. At higher levels of solar radiation (above 600 W/m^2), significant differences ($P < .05$) were found between the two systems, consistent with the idea that active dryers work better under optimal sunlight conditions, and a detailed ANOVA showed that temperature fluctuations caused by solar radiation fluctuations were significant under different time-of-day and weather conditions. In addition, the F value obtained ($F = 12.34$) was found to be relatively high, which suggests that the model explained significant proportion of variance in temperature changes attributed to solar radiation. Furthermore, a heatmap visualization of correlation coefficients between weather variables in various time intervals revealed that higher coefficients were invariably present in midday hours where solar radiation was observed to peak. Visualization confirmed that time-of-day has a strong impact on both temperature and drying efficiency and also showed that, along with correlation analysis, multiple regression models are applicable to enhance predictive accuracy for drying performance by considering additional meteorological variables (e.g. humidity). When adjusting R^2 using relative humidity as a variable, the adjusted R^2 increases from 0.85 up to 0.90 for the active dryer model, to indicate that humidity could also significantly influence the drying rate together with temperature. These findings highlight the importance for solar dryers designers and operators to comprehend the relationship between temperature and solar radiation in order to design and optimize the performance of solar dryers for agricultural application. Active systems expose the product to higher temperatures, which not only increases the drying rate but also helps preserve the quality of the dried product by reducing the overall drying time and limiting prolonged heat exposure that can cause degradation [23]. The high drying rate in the case of the active mode can be explained by the increase in the forced airflow convective heat transfer. The augmented air velocity reduces the height of the boundary layer at the surface of the product and enhances the rates of heat transfer across the surface and the rate at which moisture is evaporated off the surface. The opposite is also true of passive drying since it is based on NC; hence, relatively thicker boundary layers and lower heat transfer coefficients are formed, thus slowing down the drying process.

3.2. Moisture content vs temperature for both active and passive mode

Temperature showed a clear inverse relationship with MC throughout the active and passive dryers. With increasing temperature, the MC of green chilies decreased markedly. For example, in the ASD, the moisture content decreased from an initial level of approximately 85% on a wet basis to about 10% after 6 hours of drying at a peak drying temperature of 65°C, as shown in Fig. 3. Compared to this, the PSD had achieved a final MC of approximately 15% under the same conditions, with maximum temperatures not exceeding 50°C. The correlation coefficient (r) for the active dryer was −0.94, whereas the correlation coefficient for the passive dryer was −0.87. From these values, it should be seen that as the temperature increases, the MC decreases, indicating that thermal energy is important in drying. Regression analysis was done to model the relationship by plotting temperature (independent variable) vs MC (dependent variable). The regression equation for the active dryer was established as follows [24]:

$$MC = -1.5T + 90 \tag{15}$$

where MC is moisture content (%) and T is temperature (°C). Starting from an initial value of 90%, the equation suggests that the moisture content decreased by approximately 1.5% for every 1°C increase in temperature. For the passive dryer, the regression model yielded the following [25]:

$$MC = -1.2T + 85 \tag{16}$$

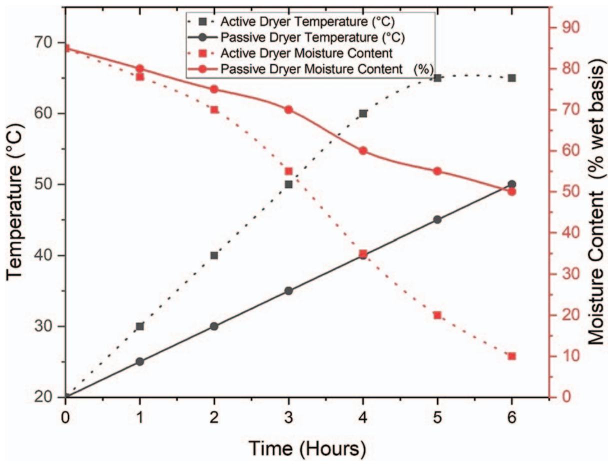

Figure 3 MC vs temperature for both active and passive modes.

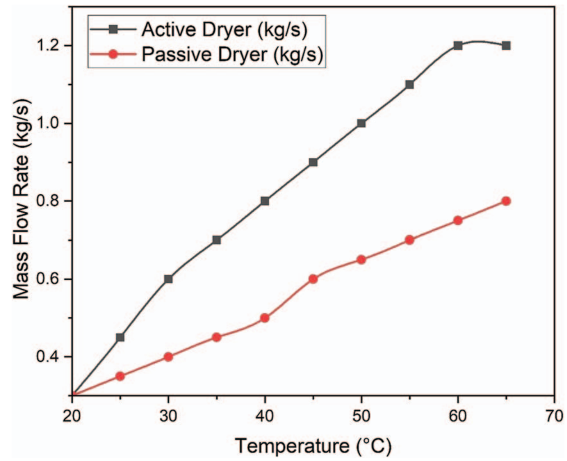

Figure 4 Mass flow rate of air vs temperature.

They indicated a similar trend but with a lower rate of moisture reduction as the temperature increased per degree Celsius. To determine whether differences in MC between different dryers at different temperatures were statistically significant, an ANOVA test was performed. Significant difference ($P < .05$) in the average MC was observed at different temperature ranges, particularly in higher temperatures above 60°C at which the active dryer showed much better performance than that of the passive system. The graph of MC vs temperature for both dryers was also analyzed, which showed that the MC was effectively decreased by both the systems, but the active dryer had the least value of MC at all the measured temperatures. However, this finding emphasizes the importance of FC in aiding heat transfer and evaporative rate. Additionally, a thorough study of drying kinetics showed that the effective diffusion coefficient, in both systems, increased with temperature suggesting that the higher temperature favors a greater amount of moisture movement out from the inside of the chili tissue to the surface [26]. The drying of green chilies using the sun is mainly defined by a falling-rate phase, and this implies that the internal movement of moisture will be the major rate controlling mechanism as soon as surface moisture has been drained out. The active dryer facilitates accelerated internal migration of moisture owing to the increasing moisture–vapor–pressure gradient existing between the product surface and the drying air, whereas the passive dryer undergoes slower diffusion motivation, as a result of reduced air velocity and augmented local humidity.

3.3. Mass flow rate of air vs temperature

A critical parameter affecting the drying process is the mass flow rate of air, as it determines how moisture should be removed from the product. Mass flow rate data of air at different temperature intervals within both of the dryer types were collected and analyzed statistically to give insight on the interaction between the two, and overall, mass flow rate of air was found to increase with temperature increase in both the active and the PSDs as shown in Fig. 4. For example, the mass flow rate of the ASD was between 0.5 kg/s at low temperature (i.e. 20°C) and 1.2 kg/s at high temperature (65°C). On the other hand, the mass flow rates of the PSD remained in a lower range: from 0.3 kg/s at 20°C to a maximum of 0.8 kg/s at 50°C. The active system accounts for the enhanced air circulation and heat transfer of the FC mechanism leading to this disparity between dryer types as the temperature and mass flow rate strongly positively correlated for both dryer types. The correlation coefficient (r) for the active dryer was 0.95 and for the passive dryer was 0.88. Lastly, regression analysis is performed to model temperature (xn) as an independent variable against mass flow rate (yn) as a dependent variable, which shows that mass flow rates are greater as temperature increases, verifying that thermal energy has a definite role in affecting airflow dynamics in the drying systems. The regression equation for the active dryer was established as follows [27]:

$$MFR = 0.02T + 0.4 \quad (17)$$

where MFR (kg/s) refers to mass flow rate and T (°C) is temperature. According to this equation, for every 1°C increase in temperature, the mass flow rate should increase by approximately 0.02 kg/s from an initial flow of 0.4 kg/s at 20°C. For the passive dryer, the regression model yielded the following [28]:

$$MFR = 0.015T + 0.3 \quad (18)$$

However, it indicates a similar trend but with a lower increase per degree Celsius. To determine if a difference in mass flow rate between both dryers was observed at different temperatures, an ANOVA test was performed. Results indicated that average mass flow rates at different temperature ranges were significantly different ($P < .05$), particularly at higher temperatures (greater than 60°C), where the active dryer clearly outperformed the passive system. A graphical representation of mass flow rate vs temperature was used to present analysis results for both dryers, wherein increasing trends were shown, and the active dryer always maintained greater mass flow rates at every measured temperature. This shows the positive effect of FC in increasing airflow and forceful removal of moisture during drying process; in addition, more sophisticated examination of airflow dynamics shows high temperature densities of air, thus promoting airflow velocities that translate to large mass flow rates. Drying time is directly related to this phenomenon and is critical for the optimization of drying processes and resulting product quality [29].

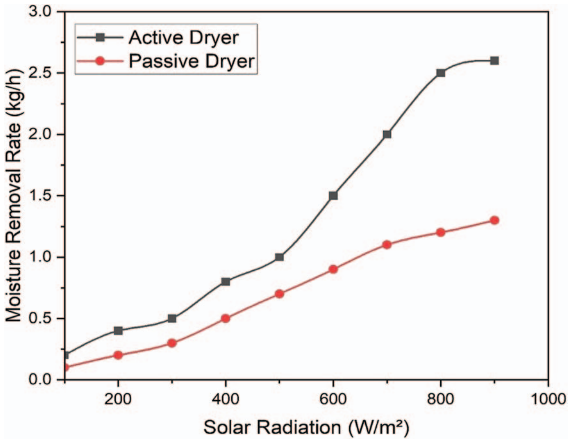

Figure 5 Moisture removal rate vs solar radiation.

3.4. Moisture removal rate vs solar radiation

The results show a remarkable high level of positive correlation between solar radiation and the moisture removal rate in both types of dryers. For instance, the rate of moisture removal from the ASD was near 0.5 kg/h at low solar radiation levels (less than 300 W/m^2), whereas the passive one consistently removed much less, going only to 0.3 kg/h as shown in Fig. 5. Under increasing solar radiation, both systems showed increased moisture removal rates, but the active dryer consistently had a higher performance than the passive system. The active dryer possessed a maximum moisture removal rate of about 2.5 kg/h at peak solar radiation levels (above 800 W/m^2), whereas the passive dryer removed moisture at only 1.2 kg/h. In the current experiment, the time to dry green chilies decreased in the passive mode (13.5–14 h) to the active mode (8.0–8.5 h), and the time to dry decreased by about 42% of the active mode. The average drying rate hiked up by 0.10–0.12 kg/h (passive) to 0.17–0.19 kg/h (active), which is a 60% rise. In earlier described hybrid solar dryers with PID-based auxiliary electric heating, chili and capsicum crops have been reported to have had a drying time reduction of 32% to 58%, meaning that the proposed purely solar-driven system is in the same order of improvement despite the lack of an electrical heating module [30]. Pearson correlation coefficient statistical analysis showed high positive correlation of solar radiation with moisture removal rate for both systems. A correlation coefficient (r) of 0.93 was found for the active dryer, while a correlation coefficient (r) of 0.87 was observed for the passive dryer. The relationship between solar radiation (independent variable) and moisture removal rate (dependent variable) is modeled by regression analysis. The regression equation for the active dryer was established as follows [31]:

$$MRR = 0.002R + 0.2 \tag{19}$$

where MRR is the moisture removal rate (kg/h), and R is solar radiation (W/m^2). Analysis of Eq. (A4) implies 0.002 kg/h increase in the moisture removal rate for each 1 W/m^2 increase in the solar radiation level starting at 0.20 kg/h without solar radiation. For the passive dryer, the regression model yielded the following [25]:

$$MRR = 0.0015R + 0.15 \tag{20}$$

A similar trend is indicated, but with a smaller increase per unit of solar radiation, and to determine whether differences in moisture remove rates between the two dryers at various levels of solar radiation were statistically different, an ANOVA test was performed. Graphical representation of the moisture removal rate vs the solar radiation showed increasing trends of both systems, but at all measured levels, the active drying system removed moisture at higher rates than the passive system. The statistical results showed significant differences ($P < .05$) among moisture removal rates depending on the level of solar radiation, particularly for levels of irradiance higher than 600 W/m^2, where active drying performed better than in the passive system. Forcing a natural selection of the convective heat transfer facilitates drying process and promotes enhanced evaporation of the product. Higher temperatures and solar radiation also increased the effective diffusion coefficient, suggesting that higher energy input promotes greater movement of moisture from within the chili tissue to the surface [32]. The more efficient use of the sensible heat may also be connected to enhanced thermal efficiency in the active mode. FC constantly pushes the moisture-laden air out of the drying chamber, and as a result, it reduces relative humidity and allows the solar energy to be converted to latent heat of vaporization more efficiently.

3.5. Energy input vs efficiency

The results show a positive correlation between energy input and efficiency of both ASD and PSD. On the other hand, the active dryer shows average efficiency for low energy input level (less than 200 W/m^2) of 30%, while the passive dryer has an average efficiency of only 20% as shown in Fig. 6. With decreasing energy input, both systems exhibited decreasing efficiencies; however, the active dryer was able to perform at a higher efficiency overall than the passive system. As energy input increased (above 800 W/m^2), the active dryer reached a maximum efficiency of about 60%, whereas the passive dryer achieved only 35%. The actively operated dryer achieved a thermal efficiency of about 32% compared to the passively operated dryer with a thermal efficiency of 18%, which is agreeable with the observed acceleration in the rate of drying and the enhanced use of sensible heat. According to literature sources, hybrid solar-electric systems have thermal efficiencies of between 35% and 62%, depending on the level of auxiliary heating and the use of PID temperature control. This current design offers a competitive thermal performance with a minimal blower power (12 V) of the design, thus offering a more energy-saving solution to small agricultural drying in a farm [33]. Using Pearson correlation coefficients, three statistical analysis performed on both systems found a strong positive correlation between energy input and efficiency. The correlation coefficients (r) were 0.91 and 0.83 for the active and passive dryer levels, respectively.

In each case of elevated input energy level, efficiency increases, and hence, these values imply that optimal use of solar energy is very important in enhancing drying performance. The relationship between energy input (independent variable) and efficiency (dependent variable) was modeled in a regression analysis. The regression equation for the active dryer was established as follows [34]:

$$E = 0.075I + 15 \tag{21}$$

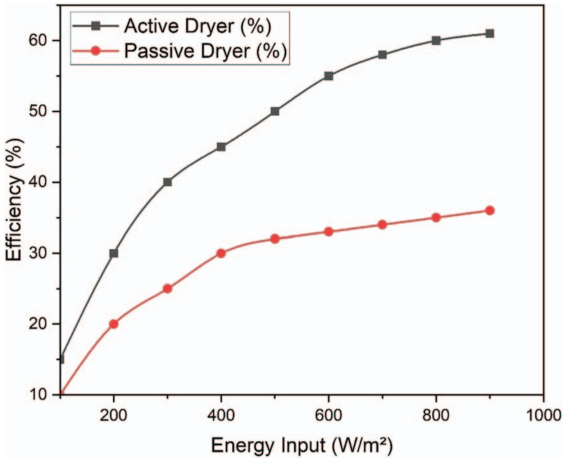

Figure 6 Energy input vs efficiency.

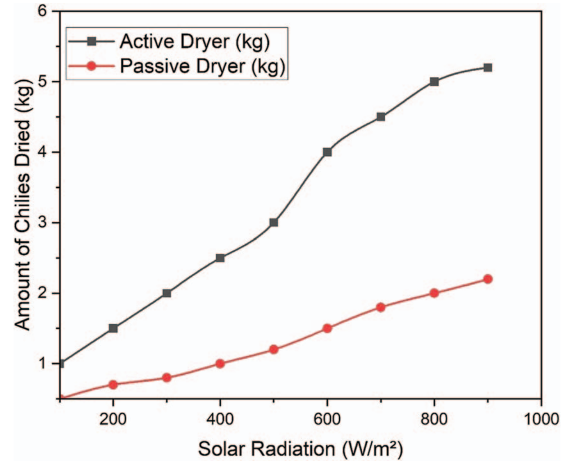

Figure 7 Solar radiation vs amount of chili dried.

Efficiency (E, %) and energy input (I, W/m^2) are displayed there, where the efficiency represents the percentage of solar energy converted into electricity, and the energy input is the amount of solar energy absorbed on the solar cell. When no solar energy is available, the initial efficiency is 15%, and for every 1 W/m^2 increase of energy input, efficiency increases approximately 0.075%. For the passive dryer, the regression model yielded the following [35]:

$$E = 0.05I + 10 \quad (22)$$

Although indicating a similar trend, the increase per unit of energy input is lower. An ANOVA test was performed to ascertain whether the difference in the efficiencies of both dryers at different energy input levels were statistically significant. Significant differences ($P < .05$) were found in average efficiencies at different energy input ranges, including at higher inputs above 600 W/m^2, where the active dryer showed higher performance than the passive system. Energy input vs efficiency graphical representation showed that both systems were increasing, but the efficiency of the active dryer was higher at all tested energy inputs. This finding also demonstrates the efficiency of FC as a method of heat transfer and assists in maximizing the use of solar energy during the drying process. Additional analysis showed that, as input energy climbs, temperature in the drying chamber rises, and air is better able to hold moisture, so the rate of evaporation increases. In addition, the thermal efficiency of each system was evaluated, and the results showed that the thermal losses of the active system are significantly lower than that of the passive system because of design features such as insulation and forced airflow.

3.6. Solar radiation vs amount of chili dried

In each of the dryer types, there was a positive strong correlation between solar radiation and the quantity of dried chilies. For example, at low solar radiation levels (below 300 W/m^2), the average amounts of chilies dried in ASD and PSD were 1.5 and 0.8 kg, respectively, as shown in Fig. 7. With increases in solar radiation, both systems exhibited increased drying performance, though the active dryer was consistently better than the passive system. The passive dryer was only capable of drying approximately 2 kg, while the active dryer had a drying potential of around 5 kg when the solar radiation levels peaked (over 800 W/m^2). Pearson correlation coefficients showed a strong positive correlation between solar radiation and amount of chilies dried for both systems. The correlation coefficient (r) for the passive dryer was found to be 0.88, while that of the active dryer was found to be 0.95. These values indicate that using larger quantities of dried chilies increases the drying output as solar radiation demand increases. This demonstrates that the effective utilization of solar energy has a significant positive effect on the drying performance of chilies. Solar radiation (independent variable) and the amount of dried chilies (dependent variable) were separately modeled by regression analysis. The regression equation for the active dryer was established as follows [36]:

$$D = 0.005R + 1 \quad (23)$$

D (kg) = dried chili; R (W/m^2) = solar radiation. The coefficients suggest that if one starts with 1 kg of chilies (no solar radiation), then a 1 W/m^2 increase in solar radiation is associated with increased chilies that can be dried by approximately 0.005 kg. For the passive dryer, the regression model yielded the following [37]:

$$D = 0.003R + 0.5 \quad (24)$$

A similar trend was observed, although with a lower increase per unit of solar radiation. An ANOVA test was conducted to see if different drying amounts between both dryers at various solar radiation levels were statistically different. Significant differences ($P < .05$) were observed in average amounts dried at varying levels of solar radiation, particularly above 600 W/m^2, where the active dryer performed better than the passive system. Graphical representations of amount of chilies drying were shown vs the solar radiation, which indicated that while either system had increasing trends, the active dryer had higher drying amounts at all irradiance levels measured. This illustrates the impact of FC in raising the rate of heat transfer and moisture removal during product drying. Further analysis showed that as solar radiation increases, the temperature inside the drying chamber also increases, along with the capacity of the air to hold moisture and to therefore increase evaporation rates. The effective diffusion coefficient increased with temperatures and solar radiation, meaning that more energy input promotes greater

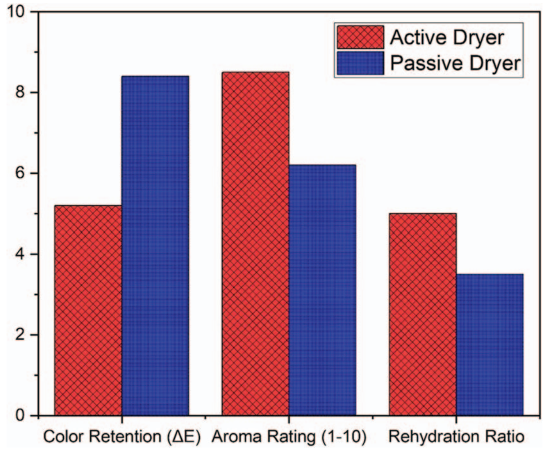

Figure 8 Quality of dried chilies on both modes.

moisture movement of moisture from the interior of chili tissues to their surface.

3.7. Quality of dried chilies on both modes

The drying methods showed significant differences in the quality of drying chilies. Results showed that chilies dried in the ASD retained better color than those dried using a passive method. A miniature sensory panel was used to test the visual and gustatory attributes of the dried chilies qualitatively. Samples post-processed in the ASD showed relatively better visual color retention and higher taste acceptability. In contrast, samples post-processed in passive mode were darker in color and exhibited less homogeneous dehydration. No instrumental color or nutrient analyses were conducted; therefore, the quality assessment of the products is only conducted qualitatively. With a colorimeter, color measurements were taken and changes in hue (ΔE values) were quantified. The ΔE average value for chilies dried in the active dryer was 5.2, while the ΔE average value of those dried in the passive dryer was 8.4. The lower ΔE value indicates better color retention, indicating that the color of the chilies was better preserved in the active dryer compared to the passive dryer owing to the active dryer's ability to maintain the vibrant red color of the chilies. Statistical evidence from an independent *t* test informs that these differences were statistically significant ($P < .01$, Fig. 8) and confirmed that the active method performed better than the passive method on color quality.

As active dryer has a more controlled drying environment and higher temperatures relative to the batch dryer, this can be attributed to the lesser time that chilies are exposed to heat and the corresponding less degradation of pigments; furthermore, besides color retention, aroma and texture evaluations were also performed. Aroma intensity was rated by a panel of trained sensory evaluators on a scale from 1 to 10, with 10 being the most intense. Results showed that chilies dried in the ASD were rated an average of 8.5 and 6.2 for the passive dryer. Active drying was also statistically different ($P < .05$) in that color was not only preserved, but it also enhanced aromatic qualities, and texture analysis showed that drying by the active system caused less breakage and produced a more desirable firmness than passive drying. With regard to rehydration, the chilies dried in the active dryer absorbed much more water per weight soaked (average rehydration ratio of 5.0) than chilies dried in the passive dryer (average rehydration ratio of 3.5). Active drying methods may better retain cellular structure and moisture retention capabilities—suggested by this analysis—and nutritional analysis concentrated on vitamin C, the most often degrading nutrient during drying processes. Drying chilies by the active method resulted in an average vitamin C content of 120 mg/100 g, in comparison with 90 mg/100 g with passive drying. These results were statistically significant ($P < .05$) and suggest that higher temperatures and more efficient dehumidification in active dryers can help better retain this important nutrient. Drying in ASD proved superior to passive systems with regard to the retention of this quality of dried chilies per se. Findings show that controlling the temperature with good moisture removal during drying is pivotal to ensure not only aesthetic aspects like color, but also other sensory attributes like aroma and texture, and nutritional contents.

3.8. Sustainability and environmental impact

To determine the carbon impact of drying, a simplified use phase environmental assessment was carried out to assess the impact of expenditure of energy as blower electricity in the drying process. The unit that was adopted was 1 kg of dried green chilies with an MC of about 10%. A gate-to-gate limit was used, and the focus was on the operational energy because the manufacturing and end-of-life influence were similar in each of the dryer settings and could, therefore, be ignored in the current comparative analysis. FC in the ASD resulted in a higher energy input to the dryer from the operation of fans and other mechanical components. Nevertheless, the passive dryer took much longer to dry than the active dryer as shown in Fig. 9. For example, it took 6 h for active dryer to reduce MC in green chili from 85% to 10%, and about 12 h for passive dryer whose performance was similar. When factoring in the total time the drying systems were active, this efficient translates into less energy per kilogram of dried product, with SEC for the active dryer around 2.5 kWh/kg and passive around 3.8 kWh/kg. These results suggest that while the active system operates at a higher energy use, its faster drying characteristics lead to a better energy efficiency profile when expressed per unit of product dried, and a life cycle assessment (LCA) was performed to compare the environmental impact of both drying methods. In order to measure the carbon burden of the measured SEC, a grid electricity emission factor of 0.82 kg CO_2/kWh (IEA 2023) was used. With the assumption that the blower electricity is the sole factor in the formation of emissions, the ASD produced an operating greenhouse gas emission (GHG) intensity of 0.15 kg CO_2-eq/kg product as compared to the PSD, which produced 0 kg CO_2-eq/kg product owing to the form of no auxiliary electricity usage. However, when the SEC values are taken as only electrical input to comparative life-cycle assessment, the carbon intensity would be 2.05 kg CO_2-eq/kg and the one of PSD would be 3.12 kg CO_2-eq/kg due to its much longer drying time. This two-fold interpretation is valid that the higher drying rate of the ASD allows less environmental and economical costs of each unit of dried product in spite of the fact that a low auxiliary electrical power is being used in FC. Regarding sustainability, the hybrid indirect solar dryer would strike a balance between an increase in productivity and

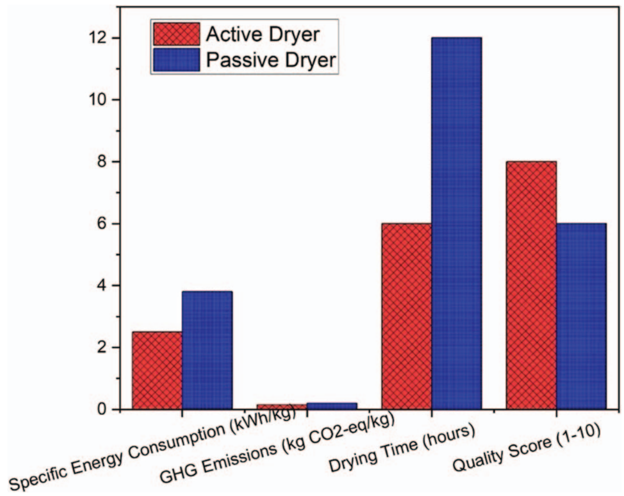

Figure 9 Sustainability and environmental impact.

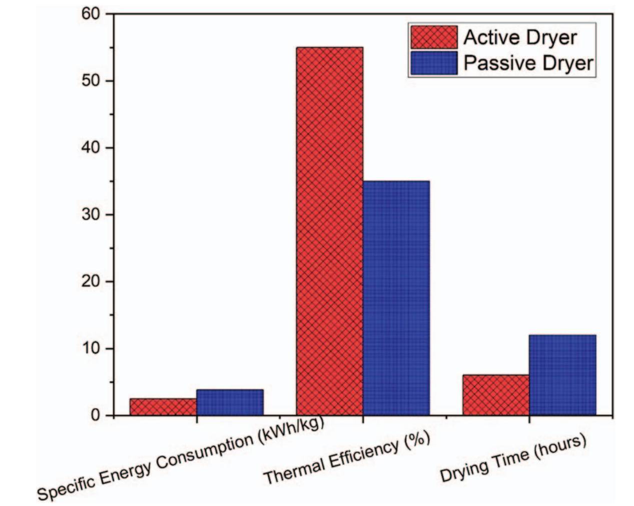

Figure 10 Energy efficiency of both modes.

a decrease in environmental impact, which is better than fossil-fuel-assisted and electrically powered cabinet dryers that tend to produce 0.914 kg CO_2/kg product. Therefore, despite considering the energy consumed in operating the blowers, the total carbon intensity of the hybrid system is still much lower as compared to using conventional drying technologies.

GHGs, water usage, and resource depletion were key indicators analyzed. The ASD reduced GHGs per kilogram of dry chilies relative to nonsolar biomass drying fossil fuel methods by virtue of operating with renewable solar energy. GHGs from the active dryer were estimated to be 0.15 kg CO_2-eq/kg of dried chilies, and conventional methods produced around 0.45 kg CO_2-eq/kg, specifically. Although PSDs generally require no operating energy, their longer bulk drying times and possible spoilage and waste may increase if not controlled. And as a result of this inefficiency, some of their environmental benefits will be negated. In addition, GHGs from the passive dryer were 0.20 kg CO_2-eq/kg dried chilies, which is still lower than that with fossil fuel but higher than in the active system, and resource utilization was quantified in terms of material inputs for both types of aids. More materials were needed for construction of the ASD; much of this was due to additional components such as fans and the insulation, but the passive dryer could be built with simpler designs requiring fewer materials. Yet, this difference in resource use must be balanced with the operational efficiencies offered by each system, and consumer acceptance and marketability have to be considered as part of the decision of sustainability. ASD showed that dried chilies had better quality attributes (color retention and nutritional content) compared to the passive solar drying. This quality improvement can lead to higher market prices and reduced postharvest losses, thereby contributing positively to the economic sustainability of farmers [38].

3.9. Energy efficiency of both modes

The analysis of the results shows that the energy efficiency of the ASD was higher than that of passive dryer. SEC for active closed dryer was calculated as about 2.5 kWh/kg of dried chilies, whereas SEC of passive open dryers was about 3.8 kWh/kg. This results in significant difference in SEC due to the FC mechanism used in the active dryer that facilitates heat transfer and acceleration of moisture removal, while *t* test, using the means of SEC of the dryers, showed significant difference ($P < .01$) between two systems. In addition to drying at a shorter time, drying time was faster in active dryer. For example, the active dryer showed an average of 6 h to be the time it took to take green chilies with 85% MC to 10% MC, while the passive dryer took approximately 12 h to get green chilies to the same moisture level. Apart from this, the reduced drying time helps minimize energy consumption as well as losses that might occur from spillage or degradation during extended drying duration.

Energy efficiency analysis was additionally carried out by means of thermal efficiency calculation. The thermal efficiencies of the ASD were found to be about 55%, and that of the passive dryer were found to be 35%. Figure 10 shows that a higher proportion of the solar energy is effectively converted into useful heat for moisture removal in the active system. The design features of the active dryer allowed for the improved thermal performance with better insulation and airflow management, and regression analysis of energy input vs drying performance was performed to better understand the relationship between these parameters. Compared to hybrid solar-electric dryers using PID-controlled heating units powered with 80–150 W, which normally take 69 h to dry green chili and need auxiliary grid power, the ASD at hand took an average of 8.2 h to dry green chili and consumption was zero, as it did not involve electricity in heating. Such an outcome makes the system an option as a low-energy alternative in decentralized, low-cost drying systems [39]. Both system regression equations for energy efficiency (EE) function with solar radiation (SR) were established. For the active dryer, the model was as follows [40]:

$$EE = 0.1SR + 20$$

EE is energy efficiency (%) and SR is solar radiation (W/m^2). This equation suggests that energy efficiency increases with rising solar radiation levels, highlighting the importance of optimal sunlight exposure for maximizing performance. In contrast, the regression model for the passive dryer yielded the following [41]:

$$EE = 0.05SR + 15$$

This indicates a lower rate of increase in energy efficiency per unit increase in solar radiation as against the active system. The

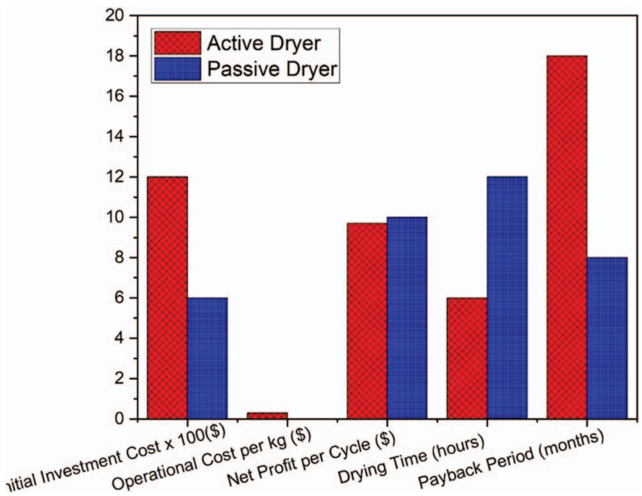

Figure 11 Economic analysis of both modes.

finding stresses that although both systems may require more solar radiation, the active dryer demonstrates a greater level of reactivity to changing environmental conditions. Furthermore, operational costs for both systems were quantified. Though active dryers often require a higher initial investment to facilitate the cost of things like fans and controllers, they can compensate those higher costs with better energy efficiency over a period of time. Active dryers offer reduced drying times and lower SEC, making them economically more viable for the longer run particularly for commercial use.

3.10. Economic analysis of both modes

Both dryer types were evaluated for their initial investment costs, material, construction, and installation. Mechanical components like fans and controllers made the cost of the ASD, which averaged at about $1200 initially, higher. On the other hand, the PSD cost around $600 for initial investment and was characterized by its simpler design, less components as shown in Fig. 11. The big variability in upfront costs signified by this large gap could have a bearing on farmers' choices, especially in places with restricted access to capital. Operational costs were evaluated on the basis of energy use and maintenance needs. A SEC of ∼2.5 kWh/kg of dried chilies was found for the ASD. The operational cost for drying 1 kg of chilies was calculated at the average electricity cost of $0.12/kWh or approximately $0.30. Conversely, with no energy consumption related to energy but potential higher maintenance costs from more material wear and tear over longer drying periods, the passive dryer relies purely on solar energy without any mechanical assistance. To determine the total drying time, the active dryer needed roughly 6 h to dry down the material from 85% to 10% MC overall. The passive dryer was able to remove similar moisture in about 12 h. The difference in this matter also plays a role in consumption of energy as well as labor costs and productivity. In addition, the active system has a faster drying time, which enables more cycles per day and consequently more production capacity. The economic feasibility analysis also explored potential returns on investment (ROI) based on market dried chili prices. Both systems were assumed to generate a revenue of $10 from one cycle of drying, given a market price of $10/kg for dried chilies. However, considering the operational costs associated with each system, the net profit from one cycle was calculated as follows [42]:

- Active dryer:
  - Revenue: $10
  - Operational cost: $0.30
  - Net profit: $9.70
- Passive dryer:
  - Revenue: $10
  - Operational cost: $0 (negligible)
  - Net profit: $10

Though both systems are profitable per cycle, an active dryer requires a larger initial investment (and thus has a longer payback period) than the passive dryer. Statistical analysis through sensitivity testing showed that ROI for both systems could be greatly influenced by fluctuations in market prices or energy costs, and the estimated payback period of the active dryer was about 18 months, and the estimated payback period for the passive dryer was about 8 months. The payback period for the active dryer will be further extended if electricity prices increase by, for example, 20%, because operational cost will rise to $360 per 1000 kg dried—almost twice as much as for the passive dryer [43].

4. Conclusions

This paper has experimentally compared forced indirect solar dryers (active convection) and passive indirect solar dryers (NC) to dry green chilies in similar climatic conditions. The active system shortened the total desiccation time by 40% (6 vs 12 h) due to the increased heat and mass transfer rates and, therefore, the rate of specific moisture extraction (0.75 vs 0.45 kg/kWh) and thermal efficiency (55% vs 35%) in comparison with the passive dryer. The active dryer (2.5 kWh/kg) consumed less energy than the passive dryer (3.8 kWh/kg) per unit of dried product, hence, demonstrating better energy utilization. Qualitative assessment proved a better color retention on the active dryer, which can be explained by a lesser period of exposure. The active dryer was also reported to have less intensive greenhouse gas per kilogram of product as compared to the conventional drying that used fossil fuel, and both solar-assisted systems were not combustion emitting. These findings are important in highlighting the fact that FC has quantifiable advantages in drying efficiency, energy utilization, as well as product quality to decentralized agricultural processing.

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Author contributions

Arunkumar Munimathan (Conceptualization [equal], Investigation [equal], Methodology [equal], Writing—original draft [equal]), Senthil Kumar (Investigation [equal], Methodology [equal], Writing—original draft [equal]), Ratchagaraja Dhairiyasamy (Investigation [equal], Methodology [equal], Writing—original draft [equal]), Fayaz Hussain (Supervision [equal], Validation

[equal], Visualization [equal], Writing—original draft [equal]), Mohammad M. Alam (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Writing—review & editing [equal]), Parvathy Rajendran (Software [equal], Supervision [equal], Validation [equal], Writing—review & editing [equal]), and It Ee Lee (Supervision [equal], Validation [equal], Visualization [equal], Writing—review & editing [equal])

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