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Thermodynamic analysis of a direct solar tunnel greenhouse dryer for drying grapes: Postharvest approach

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Abstract The drying experiment demonstrated that the grapes were effectively dehydrated, reducing their initial moisture content of 82% to a final moisture content of 16% wet (w.b.). This was achieved in 44 and 68 hours, using greenhouse and open solar drying methods, respectively. The estimated efficiency of the dryer was found to range from 11% to 39%, while the collection efficiency was determined to be between 19% and 67%. The drying kinetics of grapes was investigated and compared using regression analysis. The drying data was used to compare six thin-layer drying models. With a correlation value of 0.999 and an RMSE of 0.0134, the Thompson model describes grape dehydration behaviour quite accurately. Equations for heat and mass transport are used to forecast the temperature of the greenhouse's drying air. The equations are solved using a Gauss-Jordan elimination technique, which yields a good match with experimental temperature measurements. The pre-treatment of grape drying is also discussed, and it is true that the dryer offers a notable improvement in terms of flavor, fragrance, and color preservation. As a result, farmers may get substantially higher prices in the market.

Keywords: Grape, Greenhouse dryer, Postharvest, Solar energy, Thermal model

Introduction

Grapes, one of the oldest cultivated fruits, are consumed fresh and dried for their unique sour and rich flavour. They come in a variety of colours, including green, red, black, and purple, each with a flavour characteristic ranging from acidic to extremely sweet. Grapes are also used to make raisins, jam, juice, and wine. Azzouz *et al.* (2016) state that grapes are an excellent source of various nutrients that may positively affect health. These nutrients include resveratrol, potassium, minerals, and vitamins. Due to their high sugar

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content and high moisture content (80-85% wet basis), grapes are extremely susceptible to microbial deterioration, which can occur during storage. Value-added goods and strong export potential may be obtained from grapes, making them an important fruit crop. However, the presence of microorganisms can lead to post-harvest losses that can amount to as much as 50% of the harvested crop on a global scale. In India, the percentage of grapes lost after harvesting is 9%, and the sales in distant markets are higher than those in the local market. Dehydration is essential for preventing financial losses and may be accomplished using osmotic, solar, and mechanical drying techniques. In the past, grapes were naturally dried on the ground in hot, dry regions to create raisins. Regrettably, this approach results in irregular drying and increases the likelihood of damage caused by insects and bacteria. The use of faster, more expensive, and energy-intensive mechanical and oven-drying methods are not acceptable for small farms in India. India possesses abundant solar energy resources, with a daily irradiance range of 4 to 7 kWh/m^2. Solar drying uses heat to eliminate surplus water from a product, hence eliminating the leftover moisture. Various solar energy drying devices have been created as substitutes for traditional open-air drying, particularly in areas with enough sunlight. According to Elkhadraoui *et al.* (2015), drying systems based on configurations have been categorized into indirect, direct, and mixed modes. Pangavhane and Sawhney (2002) and Jairaj *et al.* (2009) show several common forms of sun dryers, conventional models and traditional grape drying methods. They emphasized the development work for a typical units and the drawbacks of standard shed drying technology. In their study, Srivastava *et al.* (2021) have provided a comprehensive overview of the experimental progress in solar grapefruit drying. Mathew and Venugopal (2021) also address solar dryers specifically designed for dehydrating fruitlets, vegetables, therapeutic leaves, cereals and numerous types of dryers used in various parts of the globe. El-Mesery *et al.* (2022) addressed many of the most recent breakthroughs, difficulties, and restrictions in large-scale sun drying. Greenhouse dryers are split into direct sun drying and mixed mode drying. The use of dryers is limited during the summer months because of high temperatures.

Thin layer mathematical modelling is crucial in comprehending the physics behind the drying kinetics of commodities, specifically in terms of moisture extraction. With time as the dependent variable, these models were utilized to anticipate the moisture ratio of drying commodities (Patil and Gawande, 2017). A comprehensive investigation has been carried out on the dehydration characteristics of several plant species, such as mint, amla sweets, turmeric, red pepper slices, beef, potatoes, tomato, ginger, bottle gourd, and green chilli (Sallam *et al.,* 2015; Patil and Gawande, 2018; Karthikeyan and

Murugavelh, 2018; Hamdi *et al.,* 2019; Mewa *et al.,* 2019; Ahmed *et al.,* 2020). They stated that the use of mathematical modelling in sun drying is a useful method for creating effective dryers. Furthermore, several researchers have formulated thermal models to forecast the ambient temperature within drying chambers for diverse crops, including lucerne, pineapple, cabbage, peas, and jaggery. The models offered by Farkas (2003), Bala *et al.* (2003), Jain and Tiwari (2004), and Kumar and Tiwari (2006) are dependent on the ambient temperature. There has been minimal post-harvest research on grapefruit during the last two to three decades, and the knowledge is distributed among various local and regional sources, especially in India. Consequently, research was conducted to create a medium-scale greenhouse solar drier for grape dehydration on the farm. This work aims to showcase the drying kinetics of grapes using thermodynamic analysis in the natural environment of Chandwad, India. The specific objectives were to assess the thermodynamic performance of the greenhouse in terms of drying time, moisture removal, and drying & pickup efficiency within a forced convection context, to showcase the drying kinetics of grapes by utilizing mathematical models for thin-layer drying, to create a thermal model to predict the hourly drying air temperature in the greenhouse during grape drying, and to assess impact of pre-treatment on the quality of grapes

Materials and methods

The direct solar tunnel greenhouse dryer was created and established in the Renewable Energy Division of the Department of Mechanical Engineering, located in Chandwad, India at latitude of 20.33° N and a longitude of 74.25° E. During the drying seasons from April to June 2022, four experimental trials were conducted on grapes.

Experimental design and description

The dryer is made of lightweight sheet metal and has a 4 mm thick toughened transparent cover that is inclined at a 40^0 angle as shown in Figure 1. The ambient air flows through the aperture of the first tunnel and then reaches the adjacent tunnel by an opening. Throughout the entire process, the temperature of the drying air increases as a result of the greenhouse effect, leading to the extraction of moisture from the grapes undergoing drying. A photovoltaic cell provides electricity to four fans, which ensures sufficient circulation of hot and humid air within the greenhouse. The tunnels are equipped with sliding doors at rear end to facilitate the efficient loading and unloading of produce.

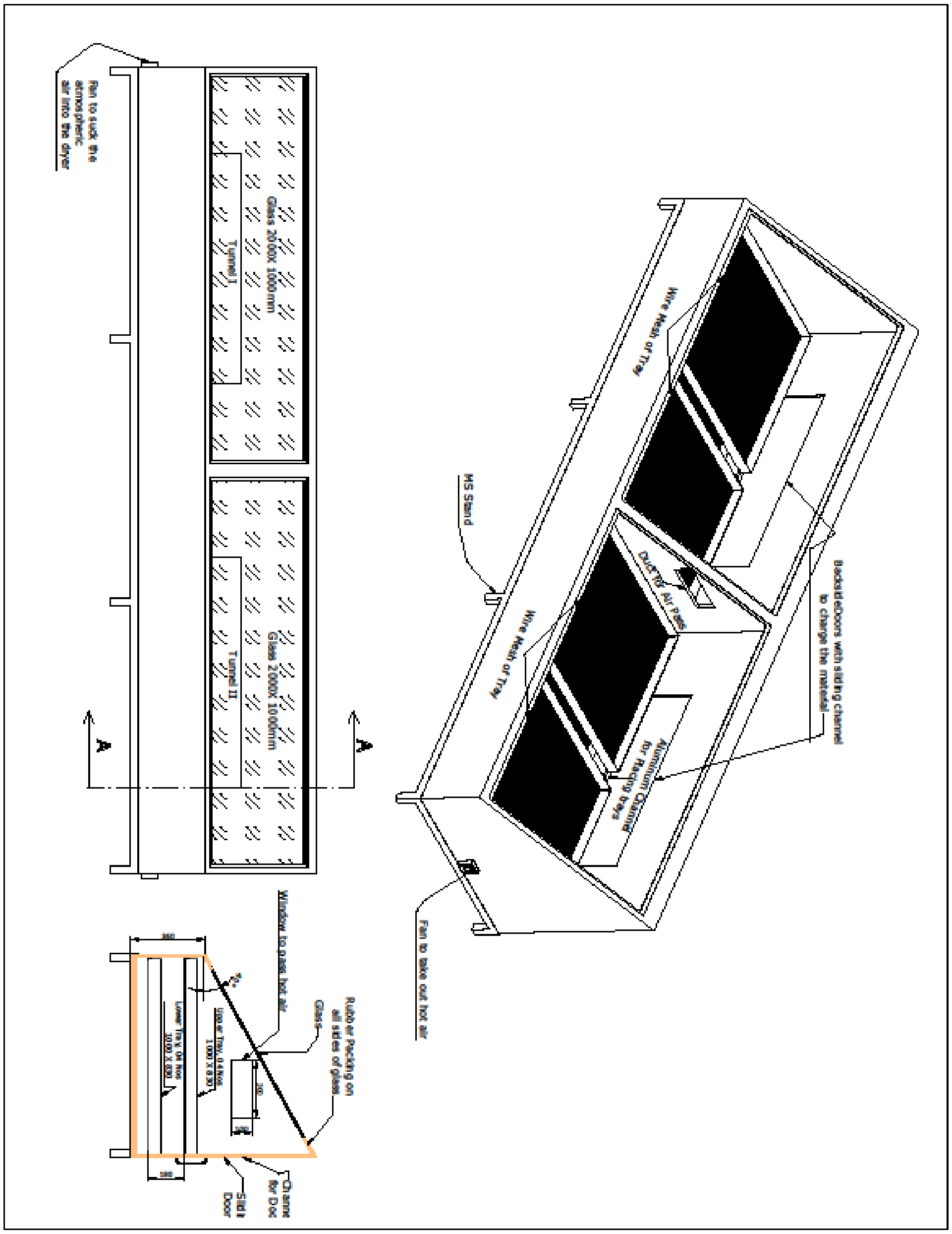

Figure 1. Schematic of solar tunnel greenhouse dryer

Sample preparation and pre-treatment

Uniform and ripe grapes were harvested from the Nashik farm, located around 67 kilometers from Chandwad's renewable energy cell. The grapes were initially selected, followed by a thorough rinsing with clean water, and subsequently received pre-treatment. The pristine grapes were submerged in a solution containing 5% K_2CO_3 and 1.5% ethyl oleate for fifteen minutes, and then washed with regular water. Prior to drying, it is necessary to do pre-treatment in order to eliminate the wax coating on the surface of the grapes. This pre-treatment enhances the rate at which moisture is removed and reduces the time required for drying (Foshanji *et al.,* 2022; Guine *et al.,* 2015). In the end, grape samples that had undergone pre-treatment were evenly distributed across all trays of the tunnel drier for the purpose of drying.

Drying experiment and instruments

At first, the dryer was tested without any load by sealing all air openings to reach a stable temperature for the drying air. Subsequently, all grapes that had undergone pre-treatment were uniformly placed on the trays of each tunnel, and the openings for air outlets were opened to eliminate moist air. Additionally, the pre-treated grapes were subjected to open sun drying to make a comparison. The temperatures of several elements, such as the surrounding air, the drying air within the greenhouse tunnel, the surface of the product, the absorber plate, and the exit drying air, were recorded using a PT-100 thermocouple with an accuracy of $\pm 0.5^0$C. An electronic weighing scale with a capacity of 6 kg (with an accuracy of ±0.01g) is utilized to measure the hourly moisture loss of grapes. The discrepancy in mass between successive measurements provided the quantity of water vapour eliminated over that timeframe. The grape drying process is carried out until the moisture content reaches the target level of 16% wet. The sun radiation intensity was quantified during experiments using a digital solar meter with a precision of 10%. The hygrometer, with a precision of ±10%, and the anemometer, with a precision of ±0.5 m/s, were used to measure the moisture and velocity of the surrounding and drying air. All the devices utilized during the experimentations were linked to a digital data logger (16C Sunpro) in order to record the essential observations. An evaluation was conducted to analyze the thermodynamic efficiency of solar greenhouse dryers compared to open sun drying based on measured observations. The evaluation focused on energy analysis, moisture reduction, and sensory analysis. Furthermore, a thermal model is included to predict the drying air temperature within the greenhouse.

Thermodynamic analysis

The dehydration process mainly depends on sun energy to extract moisture from the commodity. Therefore, it is essential to examine the energy exchange and thermal effectiveness of the airflow in the dryer. In these investigations, solar drying was regarded as a continuous and uninterrupted process. According to Elkhadraoui *et al.* (2015), the effectiveness of the solar drying system is defined as the extent to which solar radiation is efficiently employed to dry the product.

$$\eta_{\mathrm{THERMAL}} = \frac{(m \times C_P \times \Delta T)_{\mathrm{Product}} + (m_w \times H_{fg})}{Q_{\mathrm{SUPPLIED}} + \mathrm{Fan\ Power}} = \frac{(m_w \times H_{fg})}{(I \times A_{\mathrm{aperture}} + P_{\mathrm{fan}})} \tag{1}$$

Where m is mass of grapes in kg, m_w is mass of moisture in kg, Hfg is latent heat of evaporation and $A_{aperture}$ is Aperture area of dryer in m^2

Pickup/absorption efficiency refers to the proportion of moisture that is absorbed in the dryer compared to the maximum amount of moisture that the air might potentially absorb. This efficiency is calculated as follows:

$$\eta_{\mathrm{pickup}} = \frac{H_{\mathrm{outgoing}} - H_{\mathrm{incoming}}}{H_{\mathrm{as}} - H_{\mathrm{incoming}}} \times 100\ \% \tag{2}$$

Where, $H_{incoming}$ is humidity ratio of entering air, kg/kg, $H_{outgoing}$ is humidity ratio of outgoing air, kg/kg and H_{as} is humidity of inlet air entering dryer at point of adiabatic saturation, kg/kg

Mathematical modeling of drying curves

The following relation was used to create and compute the Moisture Ratio (MR) and drying curves (Yaldiz *et al.,* 2001; Doymaz, 2007) for 2000 grams grape specimen that were obtained from the trials every hour of daylight till the conclusion of drying.

$$\mathrm{Moisture\ Ratio\ (MR)} = \frac{MC_t - MC_e}{MC_i - MC_e} = \frac{MC_t}{MC_i} = e^{(-Kt)} \tag{3}$$

Where, MC_t is Moisture content on any drying time, MC_i is Initial Moisture content, MC_e is Equilibrium Moisture content, K is drying constant and t is time

To evaluate the compatibility of the drying models with the experimental data, the Coefficient of Determination (CoD) and Root Mean Square Error were employed as comparison criteria. These criteria were computed using equations (4) and (5) as proposed by Karthikeyan and Murugavelh in 2018.

$$\mathrm{CoD} = 1 - \left(\frac{\left(\sum_{i=1}^{N} \mathrm{MR}_{\mathrm{predicted}} - \mathrm{MR}_{\mathrm{experimental},i} \right)^2}{\left(\sum_{i=1}^{N} \mathrm{MR}_{\mathrm{mean}} - \mathrm{MR}_{\mathrm{experimental},i} \right)^2} \right) \tag{4}$$

$$\mathrm{RMSE} = \left(\sqrt{\frac{\sum_{i=1}^{N} \left(\mathrm{MR}_{\mathrm{predicted}} - \mathrm{MR}_{\mathrm{experimental},i} \right)^2}{N}} \right) \tag{5}$$

Where, CoD is Coefficient of Determination, $\mathrm{MR}_{\mathrm{Predicted}}$ is predicted moisture ratio, $\mathrm{MR}_{\mathrm{experimental}}$ is experimental moisture ratio, $\mathrm{MR}_{\mathrm{mean}}$ is mean moisture ratio, RMSE is Root Mean Square Error and N is number of observations

According to Yaldiz *et al.* (2001) and Doymaz (2007), the model becomes optimal when it captures both the maximum and minimum values of the CoD and RMSE, respectively.

Prediction of drying air temperature (Thermal Model)

A predictive model has been proposed to estimate the temperature of the drying air in the greenhouse, taking into account the prevailing climatic conditions. The model is based on certain assumptions outlined by Phitakwinai *et al.* (2019) and Jain and Tiwari (2004).

a) The air within the greenhouse is uniformly distributed, and its ability to absorb heat is disregarded.

b) The thin-layer drying model is the basis for all drying calculations.

c) The specific heat of the drying air, grapes, and drying cover remains constant.

d) Additionally, the greenhouse's drying air stratification is disregarded.

The toughened glass cover's energy balance is:

$$Q_{\mathrm{accumulated}} = \left(Q_{\mathrm{Convection}}\right)_{\mathrm{drying\,air-cover}} + \left(Q_{\mathrm{Convection}}\right)_{\mathrm{cover\text{-}air}} + \left(Q_{\mathrm{Radiative}}\right)_{\mathrm{grape-cover}} + \left(Q_{\mathrm{Radiative}}\right)_{\mathrm{cover}} \tag{6}$$

The variable $Q_{\mathrm{accumulated}}$ represents the amount of energy that has been collected by the toughened glass cover.

$$Q_{\mathrm{accumulated}} = M_{\mathrm{Cover}} \times C_{P\,\mathrm{Cover}} \times \frac{dT_{\mathrm{Cover}}}{dt} \tag{7}$$

Where M_{cover} is mass of cover, C_{PCover} is Specific heat of cover material in J/kgK; T_{cover} is cover temperature in K

The convective heat transfer between the tempered glass cover and the surrounding air is described as:

$$\left(Q_{Convection}\right)_{cover\text{-}air} = A_{Cover} \times h_{wind} \times \left(T_{air} - T_{Cover}\right) \tag{8}$$

Where, A_{cover} is Area of cover material in m^2, T_{air} is temperature of air, T_{cover} is cover temperature in K and h_{wind} is convection coefficient of air

The following is the specified radiative heat transmission between the toughened glass cover and the grape:

$$\left(Q_{Radiative}\right)_{grape-cover} = A_{Cover} \times \left(h_{radiative}\right)_{grape-Cover} \times \left(T_{grape} - T_{Cover}\right) \tag{9}$$

The solar radiation that the toughened glass cover absorbs is stated as follows:

$$\left(Q_{Radiative}\right)_{cover} = I \times \alpha_{cover} \times A_{Cover} \tag{10}$$

Where, I is solar radiation and α_{cover} is absorptance of cover material

Equation (11) expresses the energy balance for drying air within the dryer:

$$Q_{accumulated} = \left(Q_{Cover}\right)_{grape\text{-}drying\,air} + \left(Q_{Cover}\right)_{absorber\text{-}air} + \left(Q_{Sensible}\right)_{drying\,air\text{-}grape} + Q_{gain} + Q_{loss} + Q_{solar} \tag{11}$$

Where $Q_{accumulated}$ is the amount of heat energy that the greenhouse's drying air has gathered, and it is computed as:

$$Q_{accumulated} = M_{air} \times C_{Pair} \times \frac{dT_{air}}{dt} \tag{12}$$

Where, M_{air} is Mass of air inside the tunnel in kg, C_{Pair} is specific heat of air in J/kg K and T_{air} is temperature of air in K.

Between the grape and the drying air, convective energy transmission is calculated to be:

$$\left(Q_{Cover}\right)_{grape\text{-}drying\,air} = A_{product} \times \left(h_{convective}\right)_{grape-drying\,air} \times \left(T_{grape} - T_{drying\,air}\right) \tag{13}$$

The convective energy transport between the absorber i.e. floor and drying air is estimated as:

$$\left(Q_{Convective}\right)_{absorber\text{-}drying\,air} = A_{absorber} \times \left(h\right)_{absorber-drying\,air} \times \left(T_{absorber} - T_{drying\,air}\right) \tag{14}$$

The thermal energy (sensible) gained by drying air from the grape is:

$$\left(Q_{Sensible}\right)_{drying\,air\text{-}grape} = \rho_{grape} \times A_{grape} \times D_{grape} \times C_{Pvapour} \times \frac{dM_{grape}}{dt} \times \left(T_{grape} - T_{drying\,air}\right) \tag{15}$$

Where ρ_{grape} is density of grape product in kg/m^3, $C_{Pvapour}$ is Specific heat of water vapour in J/kgK, M_{grape} is MC of grape product, A_{grape} and D_{grape} is area and thickness of grape product in m^2 and m respectively.

The energy absorbed by the drying air within the dryer as a result of the inflow and outflow of air can be approximated by:

$$Q_{gain} = \rho_{oa} \times C_{Poa} \times V_{oa} \times T_{oa} - \rho_{ia} \times C_{Pia} \times V_{ia} \times T_{ia} \quad (16)$$

Where ρ_{ia} & ρ_{oa} is density of incoming and outgoing air of greenhouse in kg/m^3, C_{Pia} & C_{Poi} is specific heat of incoming and outgoing air in J/kgK, V_{ia} and V_{oa} is flow rate of incoming and outgoing drying air in m^3/s, T_{ia} and T_{oa} is the temperature incoming and outgoing air through the dryer in K.

The following expression estimates the total amount of heat lost from the greenhouse's drying air to surrounding air:

$$Q_{loss} = U_{Cover-ambient} \times A_{Cover} \times \left(T_{ambient} - T_{drying\ air}\right) \quad (17)$$

Where $U_{cover\text{-}ambient}$ is Overall heat loss coefficient from cover to ambient air in W/m^{2}K and $T_{ambient}$ is surrounding temperature in K.

The solar energy absorbed by the drying air inside the greenhouse can be mathematically represented as:

$$Q_{solar} = \left[\left(\left(1-\alpha_{grape}\right) \times \left(1-F_{grape}\right)\right) + F_{grape} \times \left(1-\alpha_{grape}\right)\right] \times \left(A_{Cover} \times \tau_{cover} \times I\right) \quad (18)$$

Where F_{grape} is Fraction of solar energy falling on the grape product in decimal, α_{grape} is Absorptance of grape and τ_{cover} is Transmittance of cover material

Equation (19) expresses the energy balance for the grape product:

$$Q_{accumulated} = \left(Q_{Convective}\right)_{grape\text{-}drying air} + \left(Q_{Radiative}\right)_{grape-cover} + \left(Q_{thermal}\right)_{lost} + \left(Q_{thermal}\right)_{gain} \quad (19)$$

The variable Qaccumulated represents the amount of energy that has been accumulated in the grape product and determined by eq. (20):

$$Q_{accumulated} = M_{grape} \times \left(C_{Pgrape} + C_{Pliquid} \times M_{grape}\right) \times \frac{dT_{grape}}{dt} \quad (20)$$

The convective energy transport among drying air and grape product is:

$$\left(Q_{Convective}\right)_{grape\text{-}drying air} = A_{grape} \times \left(h_c\right)_{grape-drying air} \times \left(T_{drying air} - T_{grape}\right) \quad (21)$$

The radiation heat transport among cover and grape product can be assessed by subsequent expression:

$$\left(Q_{Radiative}\right)_{grape-cover} = A_{grape} \times \left(h_r\right)_{grape-cover} \times \left(T_{Cover} - T_{grape}\right) \quad (22)$$

According to both sensible and latent heat, the thermal energy loss from the grape product is:

$$\left(Q_{\text{thermal}}\right)_{\text{lost}} = \rho_{\text{grape}} \times A_{\text{grape}} \times D_{\text{grape}} \times L_{\text{grape}} \times \frac{dM_{\text{grape}}}{dt} \qquad (23)$$

The thermal energy absorbed by the grape product from sun light can be estimated by subsequent eq. (24):

$$\left(Q_{\text{thermal}}\right)_{\text{gain}} = I \times A_{\text{Cover}} \times F_{\text{grape}} \times \tau_{\text{Cover}} \times \alpha_{\text{grape}} \qquad (24)$$

Where ρ_{grape} is density of grape product in kg/m^3 and L_{grape} is length of grape product in m.

The energy balance equation for the absorber plate/floor is given by the following expression:

$$Q_{\text{accumulated}} = \left(Q_{\text{Convective}}\right)_{\text{drying air-absorber}} + \left(Q_{\text{solar}}\right)_{\text{absorber}} \qquad (25)$$

Where $Q_{\text{accumulated}}$= energy accumulated in the absorber plate or floor & estimated by following expression:

$$Q_{\text{accumulated}} = m_{\text{absorber}} \times C_{\text{Pabcorber}} \times \frac{dT_{\text{absorber}}}{dt} \qquad (26)$$

The convective energy transmission coefficient between the drying air and absorber within the greenhouse might be approximated as:

$$\left(Q_{\text{Convective}}\right)_{\text{drying air-absorber}} = A_{\text{absorber}} \times \left(h_c\right)_{\text{absorber-drying air}} \times \left(T_{\text{drying air}} - T_{\text{plate}}\right) \qquad (27)$$

The amount of solar energy absorbed by the absorber plate can be calculated using the given expression:

$$\left(Q_{\text{solar.}}\right)_{\text{absorber}} = I \times \left(1 - F_{\text{grape}}\right) \times \alpha_{\text{absorber}} \times \tau_{\text{Cover}} \qquad (28)$$

The equation representing the mass balance for the greenhouse dryer is:

$$M_{\text{accumulation}} = M_{\text{incoming air}} + M_{\text{drying air}} + M_{\text{removed,grape}} \qquad (29)$$

Where $M_{\text{accumulated}}$= moisture accumulation of air inside the greenhouse & expressed as:

$$M_{\text{accumulated}} = \rho_{\text{air}} \times V_{\text{dryer}} \times \left(\frac{dHR}{dt}\right) \qquad (30)$$

Where, ρ_{air} is density of air in kg/m^3, HR is Humidity ratio of air inside the dryer in kg/kg and V_{dryer} is volume of drying tunnel in m^3

The following formula can be used to determine the moisture influx caused by ambient air entering the greenhouse:

$$M_{\text{incoming air}} = \rho_{ia} \times A_{ia} \times V_{ia} \times H_{ia} \qquad (31)$$

The following is the expression for the moisture discharge caused by the greenhouse's outgoing drying air:

$$M_{\text{drying air}} = \rho_{oa} \times A_{oa} \times V_{oa} \times H_{oa} \qquad (32)$$

The amount of moisture extracted from the grape product can be calculated as:

$$M_{removed,grape} = \rho_{grape} \times A_{grape} \times D_{grape} \times \frac{dM_{grape}}{dt} \tag{33}$$

Duffie and Beckman (2013) state that the following equations can be used to predict heat transfer coefficients:

$$\left(h_{radiative}\right)_{cover-sky} = \varepsilon_{Cover} \times \sigma \times \left(T_{Cover}^2 + T_{Sky}^2\right) \times \left(T_{Cover} + T_{Sky}\right) \tag{34}$$

$$\left(h_{radiative}\right)_{cover-grape} = \varepsilon_{grape} \times \sigma \times \left(T_{Cover}^2 + T_{grape}^2\right) \times \left(T_{Cover} + T_{grape}\right) \tag{35}$$

Where T_{sky} is temperature of sky in K, ε_{cover} and ε_{grape} is Emissivity of cover and grape product and σ is Stefan's Boltzmann constant

$$T_{sky} = 0.055\left(T_{ambient}^{1.5}\right) \tag{36}$$

As stated by Watmuff *et al.* (1977) following equations are used to estimate convective heat transfer coefficients:

$$\left(h_{convective}\right)_{absorber-ambient} = \left(h_{convective}\right)_{cover-ambient} = \left(h_{convective}\right)_{grape-ambient} = \frac{N_u \times K_{th}}{D_h} \tag{37}$$

$$N_u = 0.016 \times \left(Re\right)^{0.8}$$

$$Re = \frac{\rho \times V \times D_h}{\mu} \tag{38}$$

$$D_h = \frac{4 \times W \times D}{2 \times \left(W + D\right)}$$

$$\left(h_{convective}\right)_{wind} = 3 \times V_{wind} + \left(2.8\right) \tag{39}$$

Where Re is the Reynolds number, Nu is the Nusselt number, K_{th} is the Thermal conductivity of air in W/mk, μ is viscosity in Ns/m^2, D_h is the Hydraulic diameter in m, D is Average distance between floor and cover in m, W is Width of dryer in m and V_{wind} is Velocity of wind in m/s

Results

The experimental results include solar radiation intensity, moisture content removal, temperature curves, dryer efficiency, pickup or absorption efficiency, modelling of drying curve, and prediction of drying air temperature as a function of drying time.

Drying air temperatures

The experimental average entering and outgoing drying temperatures of the air of the tunnel greenhouse, as well as the outside temperature, plotted with drying time were shown in Figure 2. Based on the findings, the maximum temperature of the drying air during the test was around 68^0C. It is evident that the temperatures of the drying air at the intake and outflow increased in the morning, reached their highest level around midday, and then decreased in the evening due to variation in solar intensity. The temperature fluctuation of the dryer's drying air was measured to be $42–68^0$C, and the ambient temperature to be $29–38^0$C.

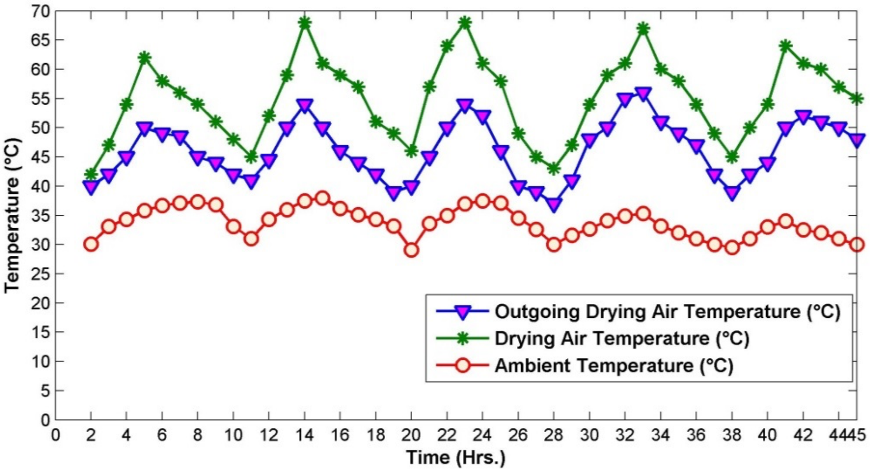

Figure 2. Varaiation of air temperature with drying time

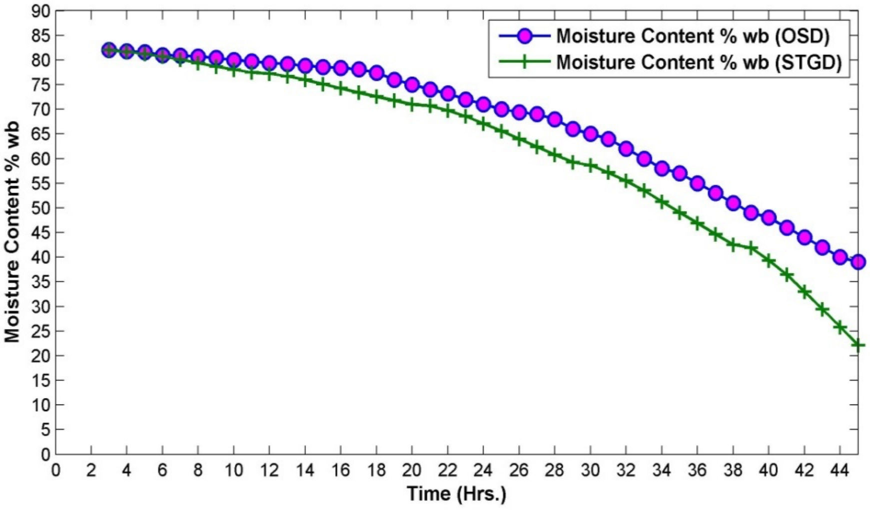

Figure 3. Variation of MC of grape against drying time

Moisture content removal

The moisture content variation of grapes against the drying time for a typical experimental set is shown in Figure 3. The grapes MC was found to gradually drop during the course of the dehydration period. The drying results showed that it took 5 and 8 days for STGD (Solar Tunnel Greenhouse Dryer) and OSD (Open Sun Drying) to dry the grapes from an initial moisture content of 82% to a final moisture content of 18% on a wet basis.

Solar Radiation intensity and efficiencies

The relationship between the changes in thermal and absorption efficiency during grape drying and the disparities in solar radiation intensity over time is shown in Figure 4. The drying efficiency was measured the overall effectiveness of the drying system. On the other hand, the pickup of absorption efficiency indicated the degree to which the drying air successfully absorbs moisture. The dryer's efficiency ranged from 11% to 39%, whereas the pickup's efficiency varied from 19% to 67%. The variation of solar intensity is observed to be in the range of 650-870 W/m^2. The observed change in solar intensity was within the range of 650-870 W/m2.

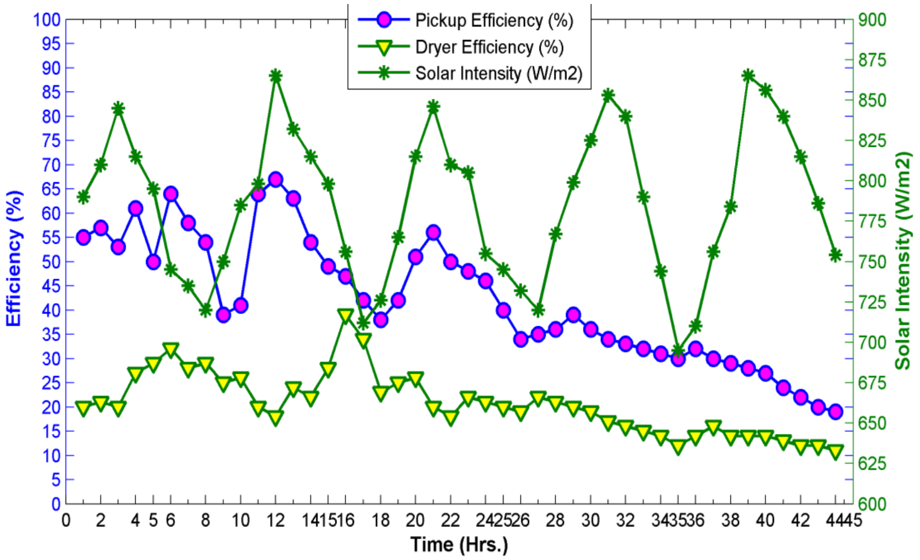

Figure 4. Variation of efficiency & solar intensity against drying time

Mathematical modelling of drying curves

The moisture content data obtained from the experiment was transformed into a dimensionless MR and then matched with the thin layer models. The regression tool is utilized for performing drying curve fitting computations, and the analysis outcomes are presented in Table 1.

Table 1. Drying curve fitting results for grape drying

Thin layer model	*Statistical Analysis*		
	Drying constant	COD	RMSE
Newton: $MR = \exp(-Kt)$	K=0.059	0.992	0.0412
Page: $MR = \exp(-Kt^n)$	K=0.0729;n=0.942	0.985	0.0456
Modified Page: $MR = \exp(-Kt)^n$	K=0.064;n=0.944	0.992	0.0412
Henderson and Pabis: $MR = a[\exp(-Kt)]$	K=0.079;a=1.2	0.98	0.0580
Wang & Singh: $t = a[\ln(MR)] + b[\ln(MR)]^2$	a=-0.5;b=-0.006	0.9935	0.0147
Thompson: $MR = 1 + at + bt^2$	a=-19;b=-3.4	0.9986	0.0134

The selected models were validated using a combination of graphical and statistical methods. The model's fitness was determined on the coefficients of determination (CoD) and root mean square error (RMSE). All chosen models exhibit a commendable fit to the experimental data, with a coefficient of determination of more than 0.96 and a root mean square error of less than 0.04. The Thomson model was chosen as the most suitable model with the highest coefficient of determination to describe the drying process of grapes in a forced convection sun drying system. The validation of the recognized model was assessed by comparing the computed moisture content under various drying settings with the experimental moisture levels. The anticipated data clustered was closely demonstatred around the straight line, indicating the suitability of the Thomson mathematical model in accurately characterizing the drying characteristics of grapes (Figure 5).

Prediction of drying air temperature within the greenhouse

The disparity between the projected and experimental drying air temperature and the drying time is illustrated in Figure 6. The temperature of the drying air in the tunnel dryer is crucial for extracting moisture from moist products. The Gauss-Jordan elimination method is utilized in solving a system of partial differential equations using known values of MC, relative humidity, grape product, temperature of the surroundings, absorber plate, and cover during a certain period. A software application called MATLAB 2010a is utilized.

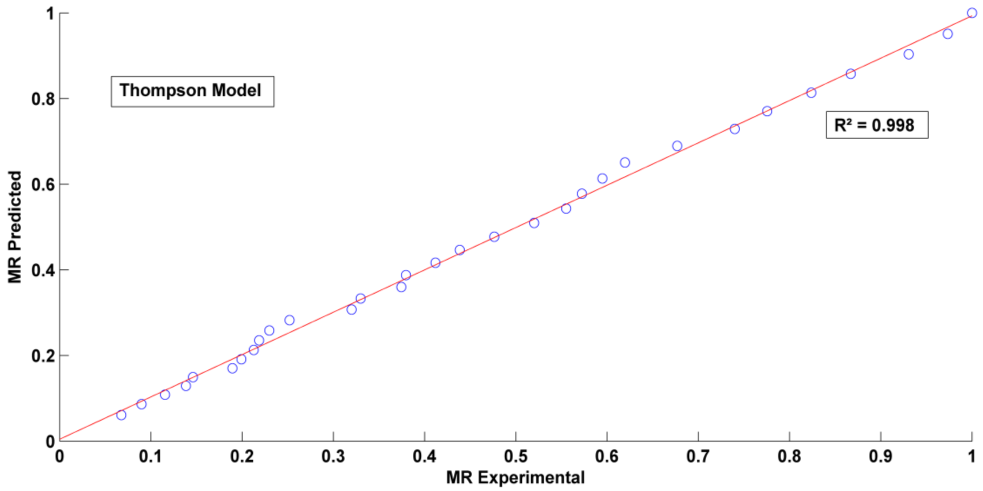

Figure 5. Thompson Thin layer drying model

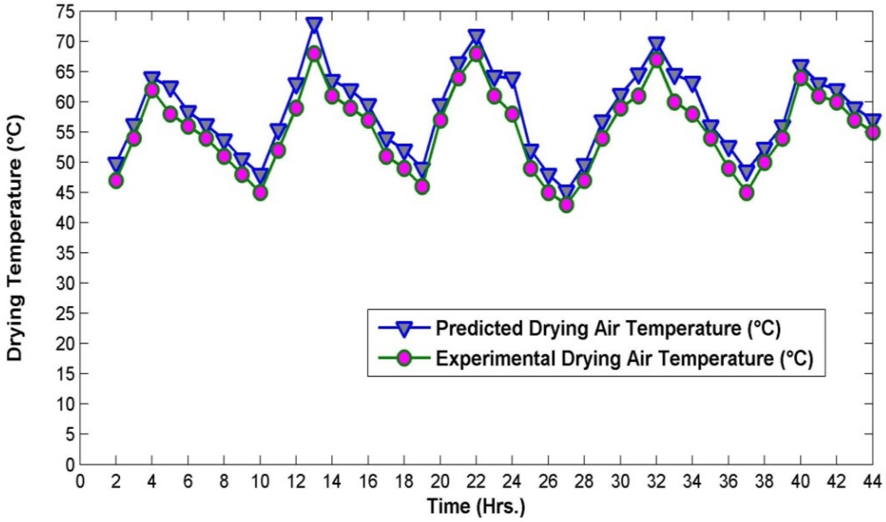

Figure 6. Variation of predicted and experimental drying air temperature

Discussion

Based on the findings of the study, specific noteworthy thermodynamic aspects can be drawn and discussed. The findings indicated that the temperature of the drying air (50–68^{0}C) within the greenhouse is optimal for extracting excess moisture from the product. The temperatures recorded by Hamdi *et al.* (2019), Phitakwinai *et al.* (2019), Elkhadraoui *et al.* (2015), and Barnwal and Tiwari (2008) are comparable to these drying air temperatures. The experimental investigation demonstrates that the STGD absorbs more moisture than open sun drying; Tiwari and Tiwari (2018) and Pardhi and Bhagoria (2013) also documented this tendency when drying sultana grapes in a greenhouse drier using a photovoltaic and mixed mode. An exponential correlation was seen between drying efficiency and drying time, with drying efficiency decreasing more significantly as the moisture content (MC) decreased. Typically, the drying efficiency is at its peak in the initial hours of the drying process and subsequently declines as the drying continues. The findings align with the study outcomes of Barnwal and Tiwari (2008), Rathore *et al.* (2012), Ubale *et al.* (2015), and Hamdi *et al.* (2019). The results demonstrate that the Thomson mathematical model effectively characterizes the drying characteristics of grapes. Yaldiz *et al.* (2001) and Hamdi *et al.* (2019) found similar findings in the drying of grapes. Furthermore, Essalhi *et al.* (2018) conducted a comparative experimental study on grapes exposed to direct sunlight and an indirect solar drier. They reported that the Midilli *et al.* (2002) model accurately characterizes the drying kinetics of grapefruit. The discrepancy in the outcome of the thin layer model is attributed to the fluctuation in weather conditions during the experimental process. The temperature of the drying air in the tunnel dryer is crucial for extracting moisture from moist products. The test results of the thermal model show that the highest temperature of the drying air reached approximately 68 degrees celsius, which is optimal for drying a variety of agricultural commodities. However, result clearly showed a temperature difference of 2-6^{0}C between the expected and actual drying air temperature. This confirms the accuracy of the thermal model in predicting the drying air temperature within the greenhouse. The temperature of the drying air in the tunnel dryer is crucial for extracting moisture from moist products. Gauss-Jordan elimination method estimates a temperature difference of 2-6^{0}C between the anticipated and experimental drying air temperature. Comparable findings were anticipated for the drying air temperature in the drying chamber during the drying of jaggery, peas, cabbage, and pineapple by Kumar and Tiwari (2006), Jain and Tiwari (2004), and Bala *et al.* (2003) respectively.

The pre-treatment of the product has a significant impact on the effective removal of the moisture, in addition to the right drying conditions and technique. The chemical pre-treatment softens the grape's thin layer and boosts its moisture permeability, thus enhancing the moisture removal rate. Based on the results, pre-drying goods can help farmers sell their raisins for a considerably higher price since it shortens the drying process by 5% while preserving qualities. The treating grapes before making raisins affected their quality. From investigation, it is observed that pre-treatment not only improves the drying rate but also enhances the quality of dried product in terms of colour, texture and taste. Thus a pre-treated grape helps the farmers to sell their raisins for considerably higher price. These results align with the findings of Adiletta *et al.* (2016), Guine *et al.* (2015), and Carranza-Concha *et al.* (2012) in terms of quality features.

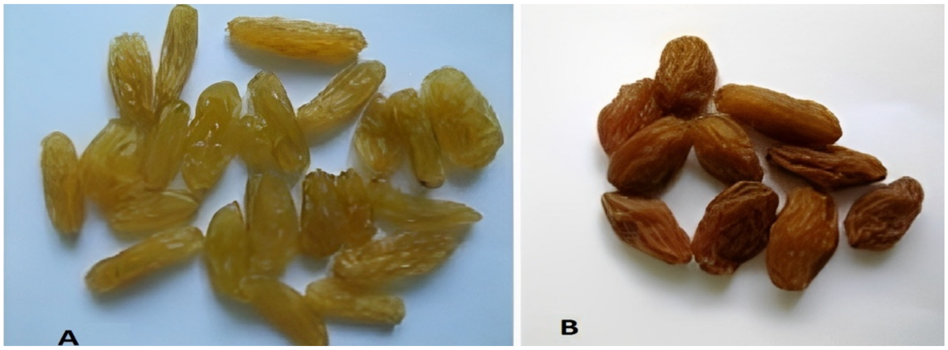

Figure 7. Quality of A. with Pre-treatment & B. without pretreatment raisins

Based on the aforementioned data, a number of significant findings may be highlighted in the following manner as compared to open sun drying, the solar tunnel greenhouse dryer reduced the moisture content by 44%. Grapes that have been pre-treated take 5% less time to dry and have better texture, flavor, and color, which increases their market value. The Thompson model was chosen as the optimal mathematical model for illustrating the drying kinetics of grapes in a thin layer. Based on the ambient temperature, thermal modeling is used to forecast the drying air temperature in the greenhouse during active mode grape drying. The new greenhouse drier enhanced the traditional method of sun-drying grapes by resolving the problem of low-quality dried grapes and the significant financial commitment associated with large-scale commercial grape dryers. Moreover, the thermodynamic study results and the dryer’s attributes, such as its lightweight design that facilitates tracking and its simple setup and disassembly at the site which indicated that commercial deployment of the dryer is possible.

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