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"Enhancing Solar Dryer Performance through Design Optimization and Computational Analysis: A Comparative Study of Configurations for Summer and Winter Seasons"

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Abstract:
This study investigates the effectiveness of different solar dryer designs for crop drying, using mathematical techniques, computational fluid dynamics, and regression analysis. The chapel type solar dryer with hot water tube shows the best results in terms of temperature distribution for the drying the crops as compared with other designs. By using hot water that is already flowing through the solar dryer, it may raise the air temperature and store heat in the water, extending its operating time and speeding up the drying process for the crops.
***Keywords:** Solar Dryer, Renewable Energy, direct/indirect drying*

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I. Introduction

The most efficient approach to meet the current energy demands of our world is to use solar energy. It significantly alleviates the use of conventional energy resources. It also offers the ideal temperature for drying purposes. [1] For centuries, people have used the power of the Sun to preserve food and other agricultural items. Agricultural items are typically dried traditionally outside under the open sky, directly in the Sun. Contrasted to drying by increasing the temperature created by traditional sources of energy, this is a common and affordable method of agricultural product preservation that is still utilised often in the majority of underdeveloped nations. [2] A natural or manufactured product can be quickly dried to remove extra moisture (or water) and bring it up to the desired moisture content. This process is known as dewatering. To function, it requires a lot of energy. Between 25 and 80 percent, but often around 70 percent for agricultural products, food frequently contains significantly more water than commodities that are ideal for long-term storage, making it especially important to reduce moisture levels..Enzymes, wild yeasts, bacterial micro-organisms, as well as moulds are slowed down by reducing the wetness percentage of foodstuffs to a specific range. Long periods of time can pass without food spoiling when it is preserved and kept in storage. Another example of drying (or reducing water content) is the practice of squeezing every remaining water content out of food until there is none. Food that has been dehydrated is rehydrated when it is time to use it, nearly restoring it to its original form. [3]

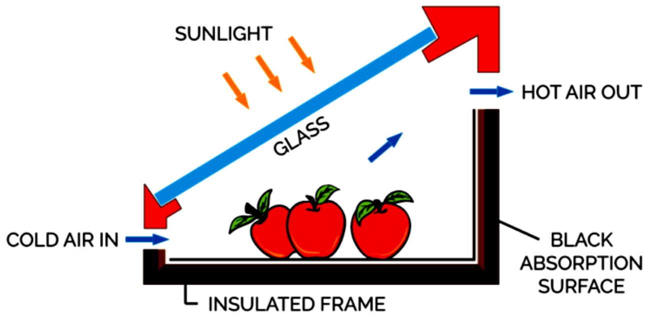


Figure 1: Concept of solar dryer

1.1 Typical solar dryer designs used:

1.1.1. Box-Type Dryers:A dryer with adjustable airflow that can be used for many different purposes is the box dryer. As materials are produced or loaded into a container (tray), they are placed inside a fixed shelf or trolley shelf in the drying chamber, where they are heated by hot air to dry.
1.1.2. Solar Cabinet dryer:The drying cabinet is the major component of a solar cabinet dryer. A glass panel solely on a single side of the cabinet allows radiation from sun to enter.
1.1.3. Chamber dryers: Solar dryers with a drying cubicles that is separate from the solar collector are referred to as chamber dryers.
1.1.4. In-House Dryers: These solar dryers are typically built on a big scale for drying agricultural products with higher capacities as well as for drying wood. The solar collector frequently serves as an integral component of the drying chamber's wall or roof in these designs.
1.1.5. Solar dryers with multi-pass and back-pass: These dryers frequently use double-pass solar collectors as their foundation. Solar drying systems can make use of three common types of solar hot air collectors: duct in front, single-pass collectors, ducts with single pass and multiple passages, and double pass solar hot air collectors.
1.1.6. Solar tent dryer: An energy-efficient, low-cost technology is a solar tent dryer. It is a straightforward solar dryer supported by two poles and composed of a sizable plastic tent.
1.1.7. Solar Tunnel Dryer: A polyhouse dryer suited for drying most food crops is the solar tunnel dryer. It comprises of a semi-cylindrical tunnel-shaped drying chamber with windows to let outside air into the dryer. To remove the damp air from the dryer, an exhaust fan is included.
1.1.8. Greenhouse Dryers: These dryers can be thought of as modified greenhouses. They have vents that are strategically placed and of the right size to manoeuvre the airflow. While mixed mode dryers are infrequently employed, essential or direct-type solar dryers make up the bulk of greenhouse dryers in use today.
The main aim of the current work is to enhance the performance of the solar dryer by changing its design using mathematical, computational fluid dynamics and regression analysis. There are following objectives of the current work.

- To design the different three dimensional CAD model of the solar dryer such as chapel type and parabolic type.
- To perform the mathematical analysis of the different parameter of the solar dryer, energy analysis of dryers, Calculation of solar radiation for selected location etc.
- To evaluate the average wind speed, maximum, minimum & average temperature, humidity and atmospheric pressure for last twelve years for the selected location.

II. Literature Review:

The best environmentally friendly and long-lasting way for preserving agricultural produce is solar drying. Product conservation will rise with the development of efficient design of drying system and agro-produce drying characteristics. Kushwah, A. et al. (2021) [1] focused on the inspection and analysis of evacuated tube aided sun dryer in alleviating the moisture present in the crops. To regulate and maintain the temperature, the hot water flow rate inside the heat-exchanger-equipped drying chamber can be changed. The thermal efficiency of the open sun drying method and ETC assisted solar dryer were evaluated. The temperature of its drying compartment rose as a result of improvements in solar dryers. The findings demonstrated that utilizing a hybrid greenhouse solar dryer produced drying times that were faster while still being comparable to OSD. The experiments are carried out on February 25 and 26, 2021, at Gwalior, India (26.2173° N, 78.1828° E), in conformity with the local environmental conditions.

Food products are dried using an indirect solar dryer, according to Benhamza, A. et al. (2021) the interrelation between the distribution of dry air temperature and the quality of the dried product is a significant factor. Computational fluid dynamics (CFD) offers an economical and adaptable method for investigating this connection, as physical experiments for parameter analysis and optimization tend to be costly and time-intensive. Thus, achieving consistent drying across items is crucial, and this can be attained through parametric assessments to establish an optimal air distribution within the drying chamber. This study utilizes a parametric approach, employing a CFD model validated through experimentation and image processing methods, to emphasize the most favourable design and operational conditions. The impact of three different mass flow rates and the introduction of a passive chimney on the distribution of drying air is evaluated using ANSYS FLUENT software. Incorporating a solar chimney resulted in a temperature increase of 7 degrees Celsius in the drying air. For mass flow rates of m = 0.0141 and 0.06 kg/s, the uniformity of air temperature showed a substantial enhancement of 21.7% and 20.3%, respectively, while a slight improvement was observed for m = 0.08 kg/s. Considering the relevant mass flow rates of m = 0.014, 0.063, and 0.087 kg/s, the average temperature exhibited increments of 16 K, 11 K, and 8 K, respectively.

Around 8000 BC, the first solar-powered drying apparatus was found in South France. Solar heat was the sole energy source available to humans before the discovery and use of biomass and wood. People in isolated small communities continue to use the sun's radiation to dry and preserve meager amounts of food, not only in the so-called third world but even in western nations. One of the first use of solar energy, according to Belessiotis, V. (2011) [3], is drying. It has been used to preserve food from the beginning of time, but it has also been used to dry other valuable goods like textiles and building supplies.

In the findings of Khanlari, A. et al. (2021) [4] experimental observations and CFD modelling revealed that the finned quadruple-flow collector was an effective concept. The quadruple-flow collector's average efficiency, which was determined experimental measurements, ranged between 73.27e78.19% and 73.27%. The energy efficiency of the mean drying chamber was also determined to vary between 44.16 - 58.38%. Significant variables for the sustainability index as well as waste exergy ratio have been obtained in the ranges of 1.93e2.73 as well as 0.52e0.56, respectively.

Due to the dryer's higher temperature than the surrounding air, food goods that are placed inside of it quickly lose their moisture content and dry out. Purusothaman, M., & Valarmathi, T. N. (2021) [5] conducted this experiment to determine the efficacy of a greenhouse solar dryer that uses insulation from the north wall. The dryer is made of wood on the outside and has PVC sheeting within. Up to 61 degrees Celsius can be used to dry food in solar dryers, hastening the process of eliminating moisture while progressively reducing the moisture content inside the solar dryer from 60% to 32%. The dryer is 1 meters long and 0.75 meters tall. On a stainless steel tray within the dryer, the food ingredients are kept for drying. To capture the most heat from the sun, a black sheet is placed at a particular distance below the tray., helping to raise the temperature inside the dryer. The drying operations for the open drying process took eight days to finish, whereas they took six days and six and a half days, respectively, for the parabolic dryer and the triangular dryer without insulation. These results demonstrated that after the food item was placed in the insulation-equipped parabolic dryer, which had the best drying performance, the drying process took the triangle dryer 5 and a half days to complete.

Ahmad, A., & Prakash, O. (2021) [6] details the development of a passive greenhouse drier, including its design and development. This project is developing and fitting a new recommended model for drying potato chips and tomato flakes in a greenhouse drier that runs in passive mode. After comparing the recommended model with six more mathematical models, it was discovered that the logarithmic model had the highest coefficient of determination for both tomato flakes and potato chips. According to statistical analysis of the predicted to experimental moisture ratio, the proposed model has the lowest root mean square error and chi square.. The outcomes demonstrated that the suggested model is more capable than earlier models of fitting curves for both potato chips and tomato flakes. Unfortunately, no more theoretical justification is given for the equation's superior curve-fitting potential.

Srinivasan, G. & Muthukumar, P. (2021) [7] offers an in-depth discussion of the design, thermal modelling techniques, and financial, energy, as well as climatic factors of solar greenhouse dryers created for dehydrating diverse agriculture based products. Performances of the various greenhouse dryer configurations/shapes are compared in terms of energy requirements.A thorough evaluation of the financial (payback period, greenhouse dryer cost, and drying cost of the product), energy-related (embodiment energy, specific energy consumption), and environmental (CO2 emission, CO2 mitigation, and carbon credit) aspects of the solar greenhouse dryer is presented based on the dryer type, mode of operation, and product dried. To achieve continuous and grid-independent drying, a thorough investigation of the selection and placement of solar PV panels and TES units in the solar greenhouse dryers is also conducted. Results of tests on the drying kinetics of various agriculturally based items are presented along with an overview of the thermodynamics and thermal modelling studies stated on forecasting the performance of solar greenhouse dryers.

Fruits and vegetables that are improperly handled suffer severe postharvest losses. Solar dryers are cited as one of the postharvest preservation techniques that is acceptable and sustainable for fruit and vegetable goods. To operate well, a solar dryer needs a number of characteristics, including a short drying time, homogenous drying air velocity, temperature, and product moisture distribution in the drying chamber. The research also looks at the well-known mathematical models for solar dryer evaluation, design, and optimisation. The efficiency of sun drying systems in terms of drying time, drying rate, and product quality variables is covered in the review. In the paper by Getahun, E. et al. (2021) [8], the most recent advancements, prospects, and difficulties in reducing of of fruit and vegetable products are covered.

Md Safri, N. A. et al. (2021) [9] conducted a thorough and in-depth analysis of solar-assisted greenhouse dryers, including passive, active, and hybrid dryers, from the perspectives of system performance, collector performance, and the drying characteristics of various crops is suggested based on past relevant studies.Crop conservation has traditionally made use of solar energy. The disadvantages of the conventional way of drying crops in the sun are overcome by the use of solar dryers. In order to give readers options concerning solar greenhouse dryers in agriculture, previous studies were thoroughly reviewed with an emphasis on crop cultivation, structural analysis, and thermal convection of greenhouse dryers.

A thorough investigation is conducted into the various dryer types, dried goods, operational circumstances, and materials used for sensible and latent heat storage. The findings are then documented and tabulated. In their work from 2021, Srinivasan, G. et al. provide a complete analysis of the multiple sensible and latent storage units and components utilized in various solar dryers, including direct type, indirect, and mixed-mode dryers that utilize both natural and forced convection. [10]. The report also provides a comprehensive explanation of the operation of thermal storage units in solar dryers.. Furthermore presented are the upcoming challenges and suggestions for the choice, application, and testing of the thermal storage unit for several solar dryers.

III. Methodology:

For the heat transfer analysis of the greenhouse solar dryer, mathematical analysis has been performed as part of this study.
The crops' initial level of moisture

$$M_{initial} = \frac{W_{initial} - W_{dry}}{W_{dry}}$$

Where:
$M_{initial}$ = crops' initial level of moisture
$W_{initial}$ = Initial weight of crops
W_{dry} = Dry weight of crops
Crops' initial level of moisture at any time 't'

$$M_t = \frac{W_t - W_{dry}}{W_{dry}}$$

Where:
M_t = Moisture present in the crops at any time
W_t = Weight of crops at any time
The drying rate (DR) of the crops

$$DR = \frac{dW}{dt} = \frac{(M_{t+\Delta t} - M_t)}{\Delta T}$$

Where:
DR = Drying rate
M_t = Crops' initial level of moisture at any time
$M_{t+\Delta t}$ = Moisture present in the crops at $t + \Delta t$
ΔT = Time difference
Moisture ratio (MR)
The moisture ratio (MR) is a dimensionless metric often used to assess how different dryers handle drying different crops.

$$MR = \frac{M_t - M_e}{M_{initial} - M_e}$$

Where:
MR = Moisture ratio
M_e = Equilibrium moisture content
Since the value of M_e is very small. As a result, it is disregarded, and MR's final value is

$$MR = \frac{M_t}{M_{initial}}$$

Calculation of convective and evaporative coefficient of the dryer
Convective heat transfer coefficient (h_c)

$$h_{con} = \left(\frac{K_a}{X}\right) \times N_u$$

Where
h_{con} = Convective heat transfer coefficient
K_a = Thermal conductivity of material W/mK
X = Characteristic length of drying tray, m
N_u = Nusselt Number
Nusselt Number can be calculated as

$$N_u = C(R_e \times P_r)^{n'}$$

Where
C = Constant
n' = Number of constant

Reynolds Number can be calculated as

$$R_e = \frac{\rho_a \times V_a \times X}{\mu_a}$$

Where
R_e = Reynolds number
ρ_a = Density of inside air Kg/m^3
V_a = velocity of inside air in m/sec
μ_a = Viscosity of air Ns/m^2
Prandtl number

$$P_r = \frac{\mu_a \times C_a}{K_a}$$

Where
P_r = prandtl number
C_a = Specific heat of inside air J/Kg-k
Amount of moisture evaporating over time from the crop surface.

$$m_e = \frac{q_{evo}}{L_{vepo}} \times A_{tray} \times t$$

Where
m_e = Amount of moisture evaporated
q_{evo} = Heat energy needed to evaporate the moisture
L_{vepo} = Vaporization's Latent heat taken as 2.26 × 10^{3}KJ/kg[2]
A_{tray} = Area of tray $(2m \times 2m)$ = 4 m^2
t = Time

IV. Result and Discussion:

In this work total four design of the solar dryer such as chapel type without hot water, chapel type with hot water, parabolic type without hot water and parabolic type with hot water have been used to perform the computational fluid dynamics and regression analysis for summer and winter season. For the computational fluid dynamic analysis transient pressure based absolute velocity formulation with turbulence model of K-epsilon, realizable, enhanced wall treatment.

4.1 Average Wind speed

An anemometer can be used to measure the wind speed, a fundamental atmospheric parameter that results from air flowing from higher pressure to lower pressure as a result of temperature changes. Wind speed has an impact on a variety of processes, including plant growth and metabolism, aviation and maritime operations, and weather forecasting. Due to the rotation of the globe, the wind directions are typically almost parallel to the isobar.

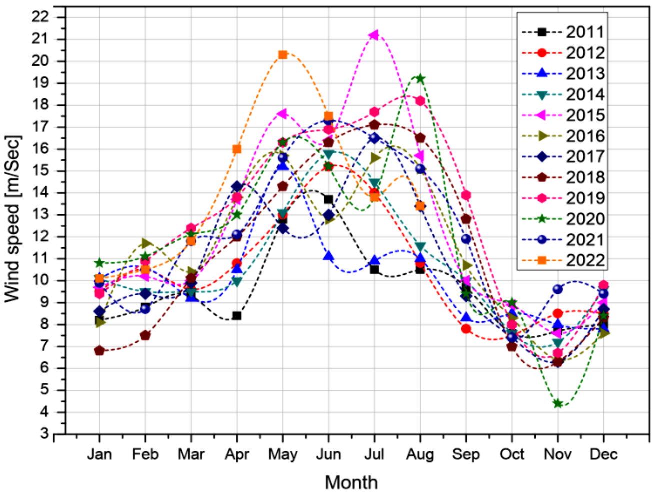


Figure 2: Average Wind speed from 2011 to 2022

4.2 The aerosol known as a cloud is a visible mass of microscopic liquid droplets, frozen crystals, or other particles suspended in the atmosphere of a planetary body or a similar environment. Water or a variety of other chemicals could be the crucial constituent of the crystals and droplets.

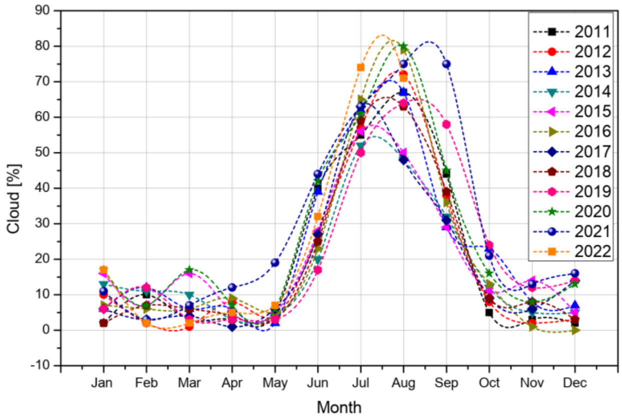


Figure 3:Cloud from 2011 to 2022

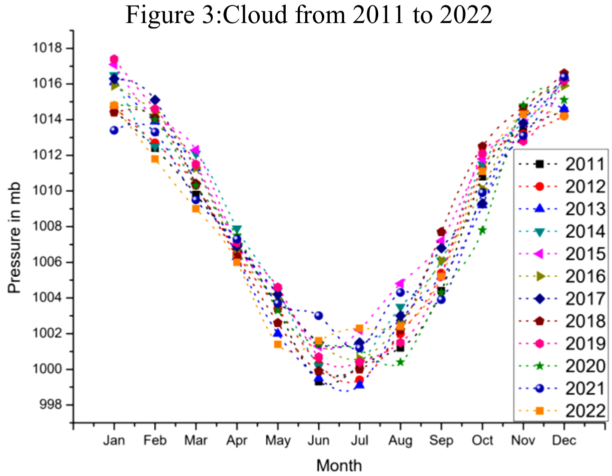


Figure 4:Average Pressure from 2011 to 2022

4.3 Maximum, Minimum & Average Temperature from 2011-2013

A measurement of the temperature at several levels of the earth's atmosphere, atmospheric temperature is affected by an array of variables, including solar radiation, humidity, and altitude.

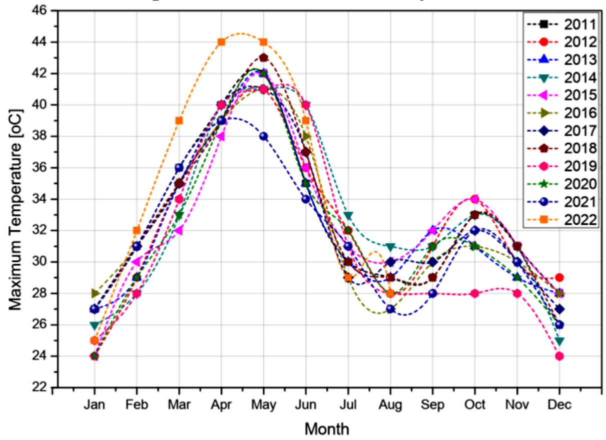


Figure 5:Maximum temperature from 2011 to 2022

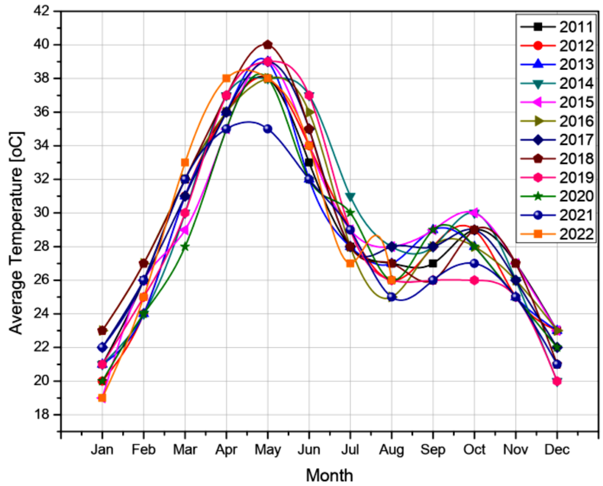


Figure 6:Average temperature from 2011 to 2022

4..4 Humidity:

Humidity refers to how much water vapor is present in the atmosphere. The gaseous form of water, known as water vapour, is normally invisible to the unassisted eye. The humidity indicates if there will be rain, dew, or fog. Humidity depends on the system's pressure and temperature. Warm air is less humid than cool air when the same amount of water vapor is present.

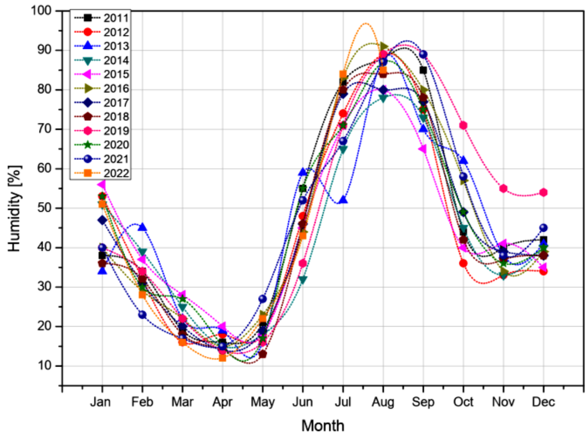


Figure 7:Humidity from 2011 to 2022

V. Calculation of Solar Radiation mean day of the month:

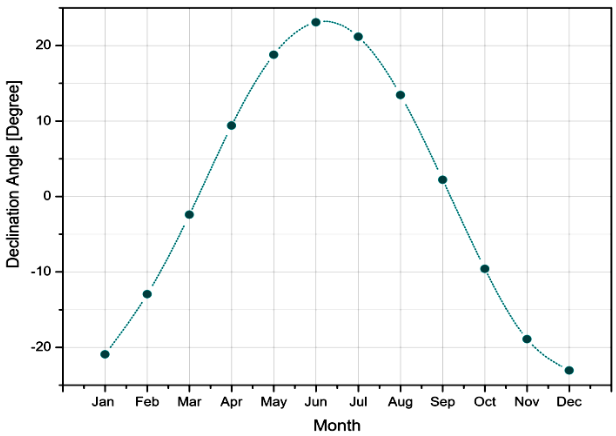


Figure 8: Declination angle of sum for the number of day throughout the year at RNTU

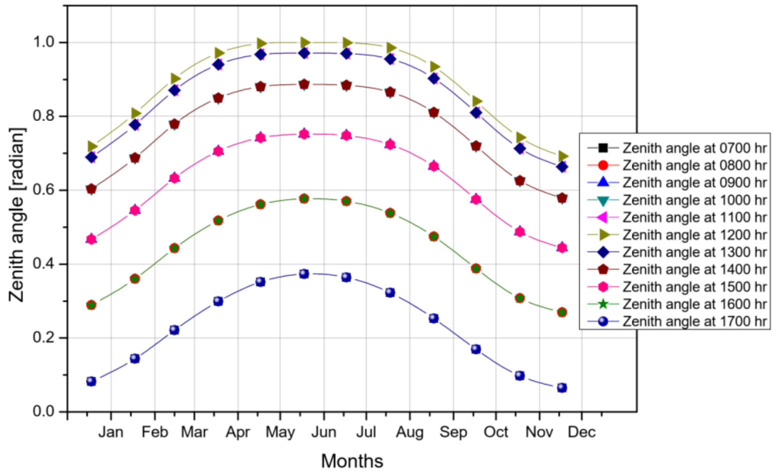


Figure 9: Zenith angle for the different solar time at the location of RNTU

RNTU's hourly global, diffuse, and beam radiation measurements on a horizontal surface

5.1Beam radiation: Beam radiation is the solar radiation that leaves the sun and descends in a straight line to the Earth's surface.

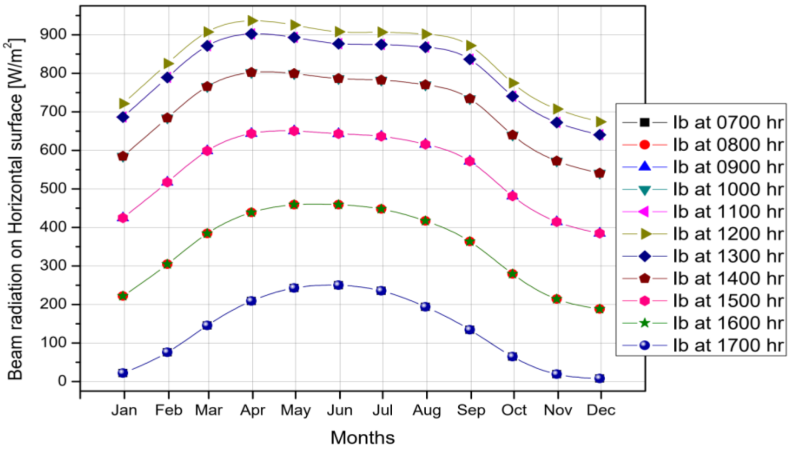


Figure 10: Beam radiation on horizontal surface for different solar time at RNTU

5.2 Diffuse Radiation: The solar radiation that strikes the planet and is refracted by atmospheric molecules and particles, but still reaches the surface.

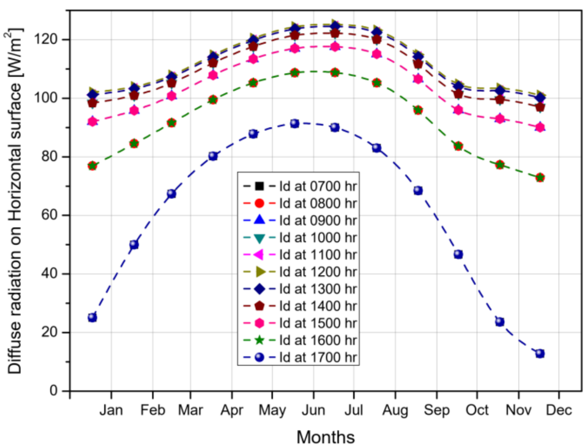


Figure 11: Diffuse radiation on horizontal surface for different solar time at RNTU

5.3Global Radiation: the total amount of radiation that hits a horizontal surface, comprising both diffuse radiation caused by sunlight that has been reflected or dispersed and direct solar radiation.

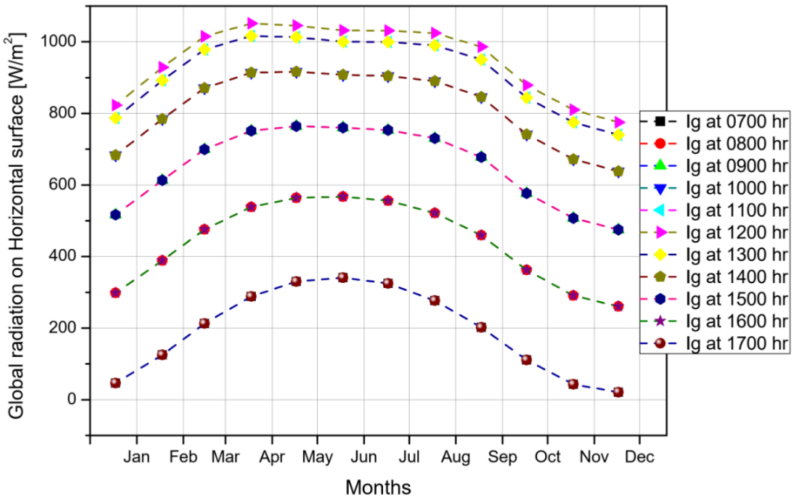


Figure 12: Global radiation on horizontal surface for different solar time at RNTU

5.4Incident solar radiation on an inclination:

It is composed of three different types of radiation: beam radiation, diffuse radiation, and radiation reflected from the surrounding area.

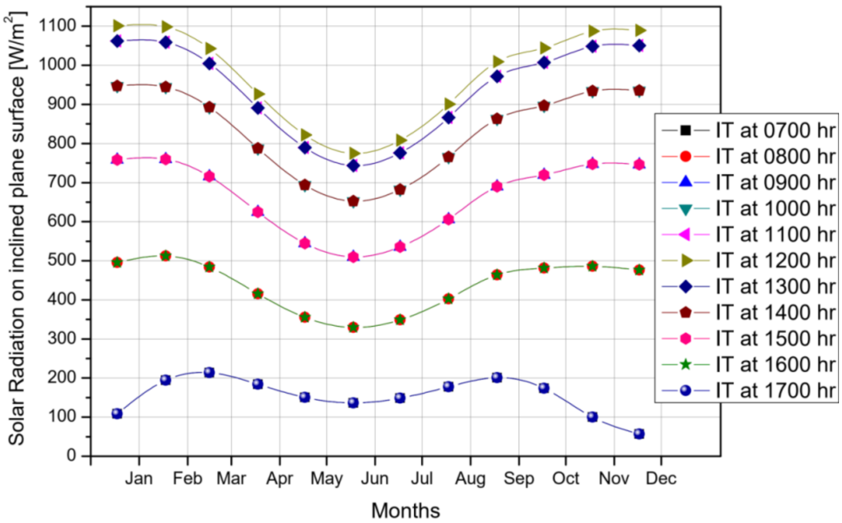


Figure 13: Solar radiation on inclined plane surface for different solar time at RNTU

VI. Monthly Average, daily diffused radiation:

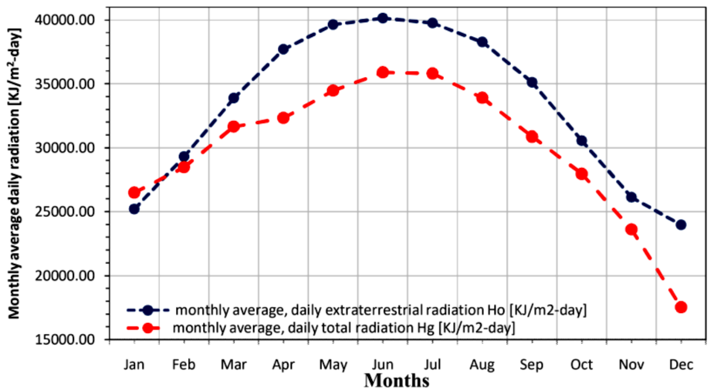


Figure 14: Monthly average daily extraterrestrial & total radiation at RNTU

6.1 Monthly Average, Hourly global radiation:

$$\frac{\overline{H}_g}{\overline{H}_o} = a + b\left(\frac{S}{S_{max}}\right)$$

Where S = monthly average daily hours of bright sunshine.

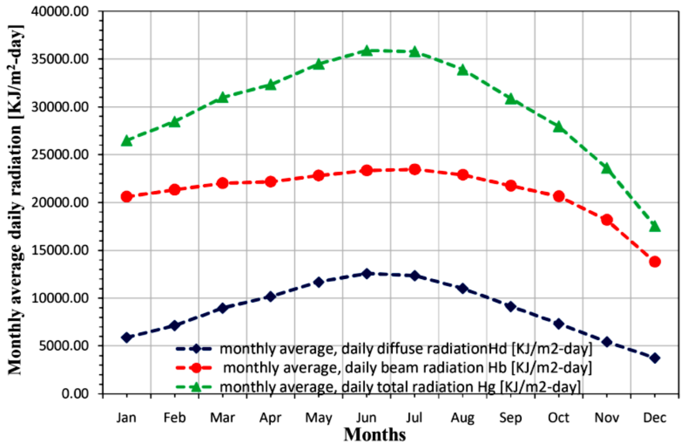
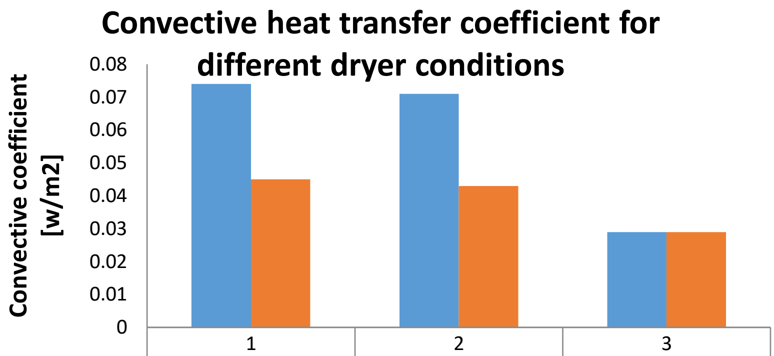


Figure 15: Monthly average daily diffuse, beam & global radiation on horizontal surface at RNTU

VII. Calculation of convective and evaporative coefficient of the dryer:

Convective heat transfer coefficient (h_{con})



	1	2	3
Dryer with ETC	0.074	0.071	0.029
Dryer without ETC	0.045	0.043	0.029

Figure 16: Convective heat transfer coefficient for different dryer conditions

Heat required evaporating the moisture in summer from different crops with & without ETC

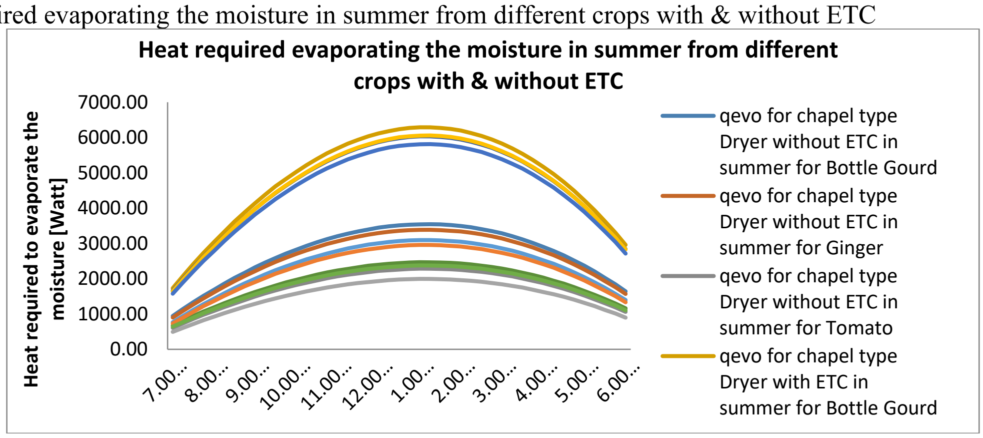


Figure 17: Heat required evaporating the moisture in summer from different crops with & without ETC

Heat required evaporating the moisture in winter from different crops with & without ETC

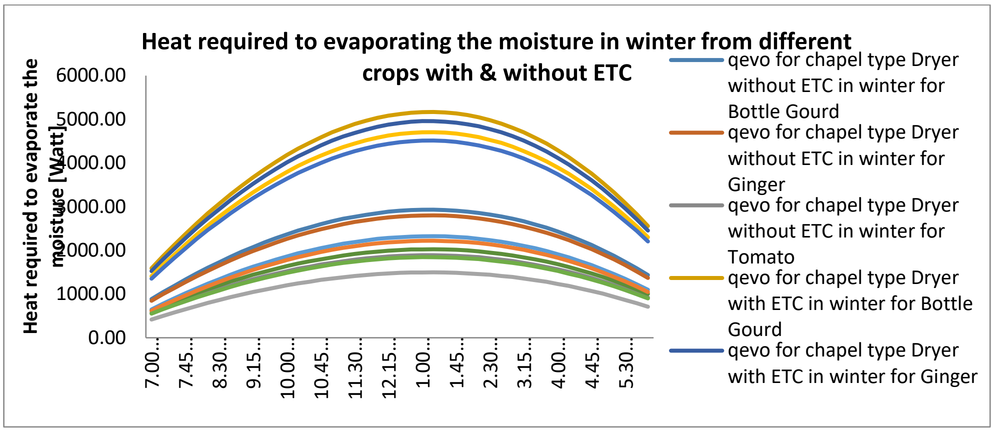


Figure 18: Heat required to evaporating the moisture in winter from different crops with & without ETC

7.1 Calculation of performance of the dryer:

Table 1: Energy in into the dryer throughout the year with and without ETC

Month	$E_{in,dryer}$ with ETC	$E_{in,dryer}$ without ETC	$E_{in,water}$
Jan	5230.97	4293.08	74.99
Feb	5849.55	4911.66	85.80
Mar	6338.46	5400.57	94.34
Apr	6513.26	5575.37	97.39
May	6445.56	5507.68	96.21
Jun	6341.08	5403.19	94.39
Jul	6333.64	5395.75	94.26
Aug	6304.17	5366.28	93.74
Sep	6126.63	5188.74	90.64
Oct	5547.58	4609.69	80.52
Nov	5145.59	4207.71	73.50
Dec	4950.79	4012.91	70.10

Table 2: Comparative results of Temperature distribution obtained from the computational fluid dynamics analysis for summer & winter

Design of solar dryer	Maximum Temperature in summer [ºC]	Minimum Temperature in summer [ºC]	Maximum Temperature in winter [ºC]	Minimum Temperature in winter [ºC]
Chapel type solar dryer without hot water	61.00	35.00	48.00	29.00
Chapel type solar dryer with hot water	65.00	35.00	51.00	30.00
Parabolic type solar dryer without hot water	54.56	36.85	39.34	27.85
Parabolic type solar dryer with hot water	63.00	34.00	47.00	29.50

VIII. Conclusion:

It has been demonstrated that putting a heat exchanger within the dryer accelerates drying. Evaporative and convective and evaporative heat transfer coefficients that are higher indicate that crop moisture evaporates more quickly. According to the findings, a heat exchanger inside the dryer shortens drying time and enhances convective and evaporative HTC. The chapel type solar dryer with hot water tubing performs best, with increased air temperature and heat storage capacity allowing for longer operation and faster crop drying. The study's main objective is to identify the optimal solar dryer design and improve its performance.

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