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Original Article

Design and Testing of a Solar Biomass Hybrid Dryer for Vegetables Drying

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Abstract *- Solar food drying is an efficient method of dehydrating food items using energy from the sun. The solar drying technique can be further improved by utilizing the biomass burner. The heat from biomass can be used as an auxiliary source during periods of low or no sunlight. This publication establishes a methodology to thoroughly design the solar-biomass system and select an appropriate biomass burner. The experimentation was carried out at Amravati (M.S., India). A solar dryer with a solar collector placed at an angle of 45 ° was selected based on local climatic conditions. The solar-biomass hybrid dryer was tested with different air velocities and with various types of vegetables. It was found that when the solar energy deficit results in incomplete or irregular drying, adding the biomass burner increases the effectiveness of the, thereby increasing the effectiveness of the system.*

Keywords *- Solar Energy, Vegetable Drying, Solar Drying, Solar Dryer, Hybrid Drying.*

1. Introduction

Drying is a method of decreasing water content to a tolerable level. Sun drying is a proven technique employed globally for ensuring the longevity of crops. Solar drying is an efficient idea for using energy from the sun [1]. Solar drying refers to the prolonged contact of a product with both solar energy and the condensing force of natural air. Solar drying provides an economical drying process; yet, it frequently yields poorer quality goods due to its reliance on climate conditions and susceptibility to contamination from dust, dirt, rain, rodents, bugs, and microbes. The dried produce can be maintained for an extended period without the risk of deterioration. The desiccated produce has multiple benefits, including improved produce quality, extended shelf life, and reduced losses following harvesting [2].Vegetables and other crops are placed directly onto the ground or a sheet of cloth during bright days for natural solar drying. The agricultural products, when subjected to direct sunlight, become polluted by dirt and bug infestations, and are also lost to birds and animals. Researchers devised multiple drying methodologies, including spray, electric, mechanical, and solar drying. These drying processes are employed globally for the desiccation of agricultural and non-agricultural items. The hybrid solar dryer possesses several advantages compared to other models, rendering it a viable solution [3]. These types of dryers not just diminish the duration of drying but additionally enhance the overall quality, color, and flavor of the items that are dried [4].

Indirect-Type Solar Drying (ITSD) is an efficient technique, as it mitigates the constraints associated with Open Sun Drying. This approach involves the transmission of heat generated by a collector to the surroundings. The warm surrounding air is then introduced into a container carrying food produce. The food items undergo heating to reduce their level of moisture [5]. The auxiliary heating and induced air circulation are advised to provide durability and enhance control, respectively. Nonetheless, several issues are linked to solar drying, namely the inconsistency of the sun's radiance through wet or overcast periods and its absence during the night. In the solar-biomass dryer, dehydration persists through non-sunlight hours using supplementary heat energy or stored thermal energy. Consequently, drying persists to protect the product from potential degradation due to microbial contamination [6, 7]. The heat storage mechanism in the dryer facilitates the continual drying operation, maintaining the drying chamber's temperature at approximately 4–20 °C above the surrounding atmosphere temperature throughout the entire night [8]. The integration of a thermal energy storage system with solar energy is beneficial because of the periodic characteristics and daily fluctuations of solar power [9]. The workings of a solar-assisted dryer throughout nighttime demonstrated that the thermal energy accumulated throughout the daylight hours can serve as an energy resource for ongoing drying of agricultural commodities, while also inhibiting the rehydration by the surroundings [10-12]. Jha et al. [7] investigated the importance of hybrid solar-driven drying

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systems in terms of managing fluctuating atmospheric and unpredictable external variables, and their influence on the dehydrating behavior of items to be dehydrated. Through analysis, it was noted that heat exchanger hybrid solar dryers were highly efficient, offered a broad drying condition range, and were appropriate for thermally delicate products. A major benefit of biofuel hybrid solar dryers is that they can utilize cheap local materials to provide energy needs. The major disadvantages associated with solar dryers include higher initial costs, which include fabrication costs, complexity in design due to simultaneous use of both solar and biomass energy, space requirements, maintenance, and energy efficiency. These potential drawbacks should be taken into account when assessing whether the hybrid solar-biomass dryer is suitable for specific applications and environments [13].

1.1. Literature Review

Certain hybrid dryers have been designed to regulate the drying air during the drying period, irrespective of sunlight, particularly at nighttime, while solar energy utilization is unfeasible, by employing an alternate biomass burner [14] or using a PV-solar integrated system [15]. Abishek Ganesh's [16] study with PCM-based heat storage systems for solar dryers encompasses the layout and development of solar cabinet dryers utilizing phase change material for storing thermal energy. Trials were conducted both using and without using drying products, utilizing forced air circulation in both standard and honeycomb configurations. The honeycomb configuration enhanced performance when using natural and forced convection, achieving 54.9% and 69.9%, respectively. Ehsan Baniasadi [17] conducted an experimental analysis of the efficiency of a hybrid solar dryer that included heat load storing. The primary objective was to create an effective and affordable dryer that sustains the process of drying post-sunset.

An Indirect Type Sun Dryer (ITSD) was designed for experiments on Capsicum and okra, with airflow facilitated by intake fans powered by solar Photovoltaic (PV) panels. The dehydration dynamics and operational characteristics of ITSD were evaluated. Capsicum and ladyfinger have diminished to ultimate water contents of 0.01 and 0.12 kg/kg, respectively, through beginning moisture contents of 8 and 10 kg/kg on a dry basis. The solar air collectors' effectiveness and effectiveness of drying for Capsicum were 74.13% and 9.15%, respectively, whereas for okra, they were 78.30% and 26.06%, respectively [5]. Mostafa M. Azam designed an autonomous hybrid solar Greenhouse Dryer (GD) incorporating photovoltaic technology and solar collectors for a small tomato processor after harvesting [18]. Assess the efficiency of hybrid gas diffusion via the modeling approach. Examine several preparatory steps on freshly picked tomatoes (whole, halved, sliced, both before and after bleaching) prior to dehydrating, determine the optimal previous treatment process, and assess the nutritional value of the end result in comparison to open sun drying. Numerous research studies have documented the modeling of enforced convective sun drying in farm products across various kinds of dryers [9, 18].

The research conducted by Samira Chouicha [19] focused on examining a localized built and fabricated indirect sun dryer to establish suitable circumstances for the safe storage of chopped potatoes. This study examined the solar-biomass dehydration of chopped vegetables through heat flow in a sun dryer, utilizing a supplementary source from a burner, which is provided by parallel-connected PV panels. The primary findings indicate that the duration of drying achieved with a single solar panel to attain the ultimate moisture weight of the potato to 0.13 kg w/kg was 3 hours. For two panels, the duration came out to be 2 hours and 45 minutes.

Asim Osman Elzubeir [20] engineered, fabricated, and operated a compact dryer to dehydrate chopped onions. The primary parts in a system are solar energy collectors, a dehydrating system, and an airflow-regulating system. This drying period averaged 20.2 hours, decreasing the original moisture content from 83% to an ultimate 5%. The solar dryer enhanced drying efficiency by 2.3 times compared to open-air solar drying. The space necessary for solar drying was approximately 25% of what was needed for equivalent air-drying efficiency.

John, n.d. [21, 22] introduced the hybrid dryer using biomass as an auxiliary source, which improved drying efficiency significantly and reduced post-harvest losses by as much as 40%. Compared to open sun drying of mangoes, which can reduce moisture only up to 16.3%, the studied hybrid system reduced the moisture as little as 3.8%. Further in the study, a mathematical model predicting the accurate performance metrics was successfully developed for other fruits. Zziwa et al. [23] introduced the sensors to monitor the temperature, humidity, and water content during tests, and pH and aflatoxin levels were tested after the test concluded. The outcome of the study showed a significant drop in drying time. Hao, W [24] used a photovoltaic and thermal system to make the system more useful. The experimentation on the drying of lemon pieces was carried out for the examination of the life-cycle of the dryer.

Kalita N. [25] compared the effectiveness of the hybrid solar biomass system to the OSD system. The author concluded that, in various medicinal herbs, the drying time was reduced by 18-50%. Other factors to be studied by the researchers were the heat utilization factor and COP of the dryer, which were also found to be improved significantly. Del Campo et al. [32], in their research, used Computational Fluid Dynamics methods to verify the working layout prior to fabrication. This facilitated the analysis of the factors related to the variables that govern this procedure, including the supply of electricity and temperature of the electrical heater, the intake of air rate, and the humidity level within the chamber used for drying. Amirtharajan et al. [33] in their experimental study, enhanced the drying process of peanuts using a solar-assisted system that combines a dryer with an air collector.

Tests were conducted under three methods: artificial, natural, and OSD —to examine factors like solar radiation, air temperature, and moisture removal. The system operated between 33°C and 58°C for 8 kg of peanuts, cutting moisture from 72 % to 18 %, and the forced convection setup proved the most efficient, showing clear potential for improving solar drying applications.

This extensive research highlights a few major findings as mentioned below:

- The main drawback of the solar dryer system is that its effectiveness completely depends on the availability of solar radiation. This limits the drying system's usability both during nighttime and during the seasons of low solar intensity. And it is where hybrid systems are useful, as they provide auxiliary sources of energy as and when required.
- The duration of viability of the product may be augmented by dehydrating it, which overcomes the problem of overproduction and ultimately food spoilage because of no demand by the customers. This leads to the year-round availability of food items.
- The dehydrated products have higher demands in other markets, where sometimes they are not easily transported if not dehydrated because of the perishable nature of the goods.

The target in the present study was to make and continually examine a solar biomass hybrid dryer (operating during the day as well as at night) with the supply of auxiliary heat via a biomass burner during night hours to reduce drying costs, enhance the quality of dried items, and inhibit mold development through the drying process.

The drying duration of such solar dryers, applicable to vegetables of the Solanoideae family, spans many days and needs reduction. Furthermore, the grade of dehydrated vegetables produced by current solar dryers is subpar due to the instability of the dehydrating temperature throughout a period of dehydrating that is influenced by fluctuations in solar intensity throughout daylight hours. The efficacy of the current solar dryers is inadequate and requires enhancement.

2. Design Methodology and Construction

This part provides a study of the mathematical formulas. Used to decide the size of the Solar collector used in a model of solar drying apparatus. These calculations are based on the estimated energy needed to dry 1 kg of vegetables. It also highlights location-specific factors and walks through the design process.

2.1. Outline

The present study focuses on finding the potential of a biomass and solar dryer hybrid system when it is used in drying applications at a selected geographical location. The modus operandi to achieve this objective has been to develop a well-designed dryer using solar energy, where heat is collected and transferred between the air and the food. This hybrid dryer is based on a hybrid drying technique, such that it will increase the efficiency of a solar dryer during low/no sunlight hours. The aim is to use a dryer for the maximum time in a day for drying. By carrying out experiments with variable conditions, drying conditions of the drying chamber at the selected location can be monitored, and energy-efficiency potential can be found.

The drying chamber transfers the collected heat to dry the entities stored within it. In this study, the area of prime focus is to maximize the transfer of heat collected from the collector to a scorching cabinet. Additionally, efforts are made to make heat energy available, which is required for drying during low solar energy times like early morning or evening hours. As much as possible, a steady supply of energy is required for uniform drying of the food [34]. The important aspect of the solar biomass hybrid system is its ability to continue drying in the absence of/low solar energy availability. To overcome the problems with the traditional solar dryer, the hybrid dryer utilizes the biomass, which is readily available in rural areas. Also, the absence of moving parts makes the dryer usable for persons without any prior knowledge.

2.2. Design Considerations of the Hybrid Solar Dryer

Based on the review of the literature, it was determined that the agricultural and forest products examined in different drying experiments and studies must have different conditions, as stated in the review. Researchers developed a variety of drying chambers and air collector designs. But in most cases, they are separate units, which makes their working and maintenance costly and difficult. Hence, in this study, efforts are made to integrate the drying chamber and solar collector. Another feature taken into consideration before the design is the fabrication of units that will work well and can be mounted both horizontally and vertically, depending on the space and location.

The hybrid dryer has been fabricated with the idea of developing a dryer that is free from complexities like those present in other hybrid dryers. The design was kept simple, and the use of any type of biomass makes the system easier for any type of user.

Solar collector-based solar dryers are designed considering the density of the material to be dehydrated (for example, 280 kg/m^3 for pepper) and the suggested thickness (for example, a single layer for pepper). Use the size of the metal mesh pallet, which can carry up to 0.7 kg of the chilies. It was planned to use three pallets with a total capacity of up to 2 kg for the test.

Before the fabrication of the solar dryer, the following items were emphasized:

1. Type of product and its drying temperature.
2. Amount and weight of items that need to be dried.
3. The product's initial and final moisture requirements should also be considered.
4. Percentage drop in the moisture content of the product.
5. Average daily solar irradiance, or flux density of radiant energy.
6. The vegetables are exposed to the sun's radiation for a specific amount of time each day.
7. Average temperature outside.
8. Materials utilized to make dryers.

2.3. Design Calculations

The following variables were examined while designing a hybrid solar dryer for drying agricultural crops based on the climatic conditions of Amravati, Maharashtra, India. Amravati is located at a latitude and longitude of 20.937424 and 77.779549, respectively. The collector, which is the main source of heat, is installed along the north-south axis and points south to receive the most direct sunlight throughout the day.

Tilt Angle (β) of the Collector/Air Heater

The tilt angle (β) of the solar collector is assumed to be,

$$\beta = 10^\circ + \text{lat}\,\phi$$

$= 30^o$

Calculations for the Area of Trays

Tray area = Overall drying amount / Amount per square meter for outdoor heating

The quantity of trays is determined from the total area by selecting the required size of the tray. Around 1.5-2 Kg of vegetables are expected to be dried inside the dryer, hence it is designed accordingly. The drying chamber is kept uninsulated intentionally so that external heat from the sun can reach the product kept inside it.

Table 1. Information on the meteorological conditions of Amravati, Maharashtra

Sr. No.	Description	Assumptions
1	Location	Amravati (Latitude - 20.937424, Longitude - 77.779549)
2	Average Daily Ambient Temperature	28°
3	Average Highest Ambient Temperature	31°
4	Average Lowest Ambient Temperature	23.7°
5	Average % RH	54
6	Mean wind velocity	3 m/s
7	Mean precipitation levels	2.46 mm/day
8	Mean solar irradiance on a horizontal plane	6.01 $KWh/m^2/day$
9	Avg Solar Radiation on Tilted Surface (Tilt angle = 90˚)	3.97 $KWh/m^2/day$
10	Mean diffuse solar irradiance on a horizontal plane	2.24 $KWh/m^2/day$
11	Mean Daylight Hour	11.97 Hrs

Source: NASA - (POWER)

Table 2. Specifications of the material intended for drying in the solar dryer, Chilli (Capsicum annum)

Sr. No.	Description	Assumptions
1	Product	Chilli
2	Farming period	Mid-July to September-End & February to March
3	Moisture present at the start of the experiment	82%
4	Moisture present at the end of the experiment	6%
5	Maximum admissible temperature during the drying process	63°C
6	Material thickness	2-3mm

Table 3. Specifications of the material intended for drying in the solar dryer, Potato

Sr. No.	Description	Assumptions
1	Product	Potato
2	Cultivation duration	Jan to Feb (Autumn crop) April to May (Spring crop)
3	Moisture present at the start of the experiment	82%
4	Moisture present at the end of the experiment	9%
5	The maximum admissible temperature during the process of drying	68°C
6	Material thickness	2 mm [19]

Table 4. Specifications of the material intended for drying in the solar dryer, Tomato

Sr. No.	Description	Assumptions
1	Product	Tomato
2	Cultivation duration	Jan to Feb (Autumn crop) April to May (Spring crop)
3	Moisture present at the start of the experiment	80%
4	Moisture present at the end of the experiment	9%
5	The maximum admissible temperature during the process of drying	65°C [30]
6	Material thickness	2 mm [19]

Table 5. Specifications of the material intended for drying in the solar dryer, Eggplant

Sr. No.	Description	Assumptions
1	Product	Eggplant (Solanum melongena)
2	Cultivation duration	July, August, and September
3	Moisture present at the start of the experiment	90%
4	Moisture present at the end of the experiment	6%
5	The maximum admissible temperature during the process of drying	67°C [31]
6	Material thickness	3-5 mm

2.3.1. Moisture Removal Quantity (Mq)

The amount of water that is taken out from available vegetables results in lowering their original moisture level to the desired concluding value in order to improve their lifespan. It can be calculated using the following formula:

$$Mq = Mpw\,(Mic - Mfc)/(100 - Mfc)$$

Where

M_q = Quantity of moisture taken out in kg

M_{pw} = Original weight, kg

M_{ic} = Moisture present at the start of drying on a wet basis %

M_{fc} = Moisture present at the end of drying on a wet basis %

$$Mq = 2\,(82 - 6)/(100 - 6) = 152/94 = 1.62 \text{ kg (For Chilli)}$$

$$Mq = 2\,(82 - 9)/(100 - 9) = 146/91 = 1.6 \text{ kg (For Potato)}$$

$$Mq = 2\,(80 - 9)/(100 - 9) = 142/94 = 1.56 \text{ kg (For Tomato)}$$

$$Mq = 2\,(90 - 6)/(100 - 6) = 168/94 = 1.79 \text{ kg (For Eggplant)}$$

Maximum M_q was found for eggplant,
Therefore,

$$Mq = 1.79 \text{ kg}$$

2.3.2. Heat Requirement for Moisture Removal (Q)

The water content in the vegetables, which was found using equation (1), must be taken out. The amount of heat necessary for this moisture removal was estimated using the following equation –

$$Q = Mq \; x \; Hvap$$

Where Q = The energy demand associated with the drying process,

H_{vap} = Latent heat of vaporization of water (kJ/kg of H_2O)

The latent heat of vaporization (Hvap) is evaluated using the expression formulated by (Youcef-Ali et. al. 2001) [26]

$$Hvap = 4.186 \text{ X } 103(597 - 0.56\,Tpr)$$

Where T_{pr} = Temperature of the Product, °C

Note -For chili, the highest temperature allowed for drying (T_{pr}) is considered to be 67 °C.

Therefore,

$$Hvap = 4186 (597 - 0.56 \text{ x } 67)$$
$$Hvap = 2341983.28 \text{ KJ}$$

Hence,

$$Q = Mq \text{ x } Hvap$$
$$Q = 1.79 \text{ x } 2341983.28$$
$$Q = 4208934 \text{ KJ}$$

2.3.3. Mean Rate of Drying

The drying rate (Dmr) was evaluated using the following equation –

$$Dmr = Mw/Tdr$$

Where, D_{mr} = Mean Rate of drying, Kg/hr
T_{dr} = Time for drying, hrs

Time required for drying is assumed to be 12 hrs

$$Dmr = 1.79/12 = 0.15 \text{ kg/hr}$$
$$Dmr = 0.15 \text{ kg/hr}$$

2.3.4. Air Requirement for Dehydrating (M_d)

The amount of air essential for the dehydrating process of vegetables is evaluated through the application of the following equation [27].

$$Md = DR(wo - wi)$$

Where
M_d = Air Mass Requirement for Drying, kg/hr
w_{ih} = Proportion of mass of water vapour to the mass of air at start, kg_{water}
w_{fh} = Proportion of mass of water vapour to the mass of air at the end, kg_{water}

Now, Drying Ratio = 0.151

$$wih = 0.0098 \text{ Kg of water/kg of dry} - \text{air (dry)}$$
$$wfh = 0.02 \text{ Kg of H2O / kg of dry} - \text{air (saturated)}$$
$$Md = 0.15(0.02 - 0.0098)$$
$$Md = 14.7 \text{ kg /hr}$$

2.3.5. Heat Content [7]

The value of enthalpy for moist air [28]

$$h = 1006.9 \text{ T} + w [2512131 + 1552.4 \text{ T}]$$

Therefore, the starting and end enthalpy was calculated using-

$$hi = \{1006.9 \text{ X } 28 + 0.0098 [2512131 + (1552.4 \text{ X } 28)]\} / 1000$$
$$hi = 52.2 \text{ KJ/kg}$$

Also

$$hf = \{1006.9 \text{ X } 68 + 0.02 [2512131 + (1552.4 \text{ X } 68)]\} / 1000$$
$$hf = 119.78 \text{ KJ/kg}$$

2.3.6. Total Heat Energy Used (Qr)

The effective amount of heat absorbed by the drying air can be determined using the following equation.

$$Qr = Mr .(hf - hi).\text{Tdt}$$

Where Q_r = Energy needed, KJ
M_r = Rate of flow of mass of air, kg/hr
h_o = Initial drying heat content
h_f = Final drying heat content
T_{dt} = Duration for drying, hrs

$$Qr = \{14.47 \text{ X } (117.70 - 51.8) \text{ X } 8\} / 1000$$
$$Qr = 11.73 \text{ KJ}$$

2.3.7. Effective Aperture Surface Area of the Solar Collector

Based on the complete energy demand and the total incident solar incidence, the area of aperture of the collector is determined using the following expression:

$$Qr = Ap . I . Ꞃd$$

Where
Q_r = Heat-energy requirement, KJ
I_a = The annual average cumulative solar irradiance incident on all glazed wall surfaces, KJ/m^2
A_p = Area of aperture surface, m^2
$Ꞃ_d$ = Solar dryer Efficiency is 30% to 50% [27]
Considering,
Q_r = 11.73 KJ
I_{aw} = 6.34 KJ/m^2
Ꞃ = 0.3 Ꞃ

$$Ap = QrIaw \text{ x } Ꞃd = 11.73\ 6.32 \text{ X } 0.3$$
$$Ap = 1.9 \text{ m2}$$

Table 6. Calculations for Design: Capsicum annuum

Particular	Observations	Measures
Initial weight: Chili *(M_i)*	2	Kilogram
Original water present prior to the dehydration (*Mic*)	82	%
Remaining water following the dehydration (*Mic*)	6	%
Moisture quantity that is extracted from an item *(Mq)*	1.62	Kilogram
Thermal state of the surroundings *(T_a)*	27	Degrees Celsius
Thermal state of the sample*(Tpd)*	67	Degrees Celsius

Enthalpy of vaporization	2351359.9	Kilojoules/ Kilogram
Thermal energy needed to evaporate water *(Q)*	4208934	Kilojoules
Original proportion of mass of water vapour to the mass of dry air (w_0)	0.0098	Kilogram/ Kilogram
Ultimate ratio of mass of water vapour to the mass of dry air (we)	0.02	Kilogram/ Kilogram
Heat content at surrounding conditions (k)	52.2	Kilojoules/ Kilogram
Heat content at resultant conditions (h_i)	119.78	Kilojoules/ Kilogram
Dehydration period *(ta)*	12	Hours
Mean dehydration speed	0.15	Kilogram/ Hour
Amount of flow required to desiccate (m)	14.47	Kilogram/ Hour
Operational performance *(w)*	0.5	
Overall latent heat of vaporization (L_o)	11.73	Kilojoules
Yearly mean irradiance on shiny surfaces (I_{aw})	940	Joules/ Second -m^2
Yearly mean irradiance on shiny surfaces (I_{aw})	6.32	Kilojoules/ Hour -m^2

Table 7. Calculations for Design for Potato

Particular	Observations	Measures
Initial weight: Potato (M_i)	2	Kilogram
Original water present prior to the dehydration (*Mic*)	82	%
Remaining water following the dehydration (*Mic*)	9	%
Moisture quantity that is extracted from an item *(Mq)*	1.6	Kilogram
Thermal state of surroundings (T_a)	27	Degrees Celsius
Thermal state of the sample*(Tpd)*	68	Degrees Celsius
Enthalpy of vaporization	2351359.9	Kilojoules/ Kilogram
Thermal energy needed to evaporate water *(Q)*	4208934	Kilojoules
Original proportion of mass of water vapour to the mass of dry air (w_0)	0.0098	Kilogram/ Kilogram
Ultimate ratio of mass of water vapour to the mass of dry air (we)	0.02	Kilogram/ Kilogram
Heat content at surrounding conditions (k)	52.2	Kilojoules/ Kilogram
Heat content at resultant conditions (h_i)	119.78	Kilojoules/ Kilogram
Dehydration period *(ta)*	12	Hours
Mean dehydration speed	0.15	Kilogram/ Hour
Amount of flow required to desiccate (m)	14.47	Kilogram/ Hour
Operational performance *(w)*	0.5	
Overall latent heat of vaporization (L_o)	11.73	Kilojoules
Yearly mean irradiance on shiny surfaces (I_{aw})	940	Joules/ Second -m^2
Yearly mean irradiance on shiny surfaces (I_{aw})	6.32	Kilojoules/ Hour -m^2

Table 8. Calculations for Design for Tomato

Particular	Observations	Measures
Initial weight: Tomato *(M_i)*	2	Kilogram
Original water present prior to the dehydration (*Mic*)	82	%
Remaining water following the dehydration (*Mic*)	6	%
Moisture quantity that is extracted from an item *(Mq)*	1.56	Kilogram
Thermal state of the surroundings *(T_a)*	27	Degrees Celsius
Thermal state of the sample*(Tpd)*	67	Degrees Celsius
Enthalpy of vaporization	2351359.9	Kilojoules/ Kilogram
Thermal energy needed to evaporate water *(Q)*	4208934	Kilojoules
Original proportion of mass of water vapour to the mass of dry air (w_0)	0.0098	Kilogram/ Kilogram
Ultimate ratio of mass of water vapour to the mass of dry air (we)	0.02	Kilogram/ Kilogram
Heat content at surrounding conditions (k)	52.2	Kilojoules/ Kilogram
Heat content at resultant conditions *(h_i)*	119.78	Kilojoules/ Kilogram
Dehydration period *(ta)*	12	Hours
Mean dehydration speed	0.15	Kilogram/ Hour
Amount of flow required to desiccate (m)	14.47	Kilogram/ Hour
Operational performance *(w)*	0.5	
Overall latent heat of vaporization *(L_o)*	11.73	Kilojoules
Yearly mean irradiance on shiny surfaces (I_{aw})	940	Joules/ Second -m^2
Yearly mean irradiance on shiny surfaces (I_{aw})	6.32	Kilojoules/ Hour -m^2

Table 9. Calculations for Design for Eggplant

Particular	Observations	Measures
Initial weight: Eggplant *(M_i)*	2	Kilogram
Original water present prior to the dehydration (*Mic*)	82	%
Remaining water following the dehydration (*Mic*)	6	%
Moisture quantity that is extracted from an item *(Mq)*	1.79	Kilogram
Thermal state of the surroundings *(T_a)*	27	Degrees Celsius
Thermal state of the sample*(Tpd)*	67	Degrees Celsius
Enthalpy of vaporization	2351359.9	Kilojoules/ Kilogram
Thermal energy needed to evaporate water *(Q)*	**4208934**	Kilojoules
Original proportion of mass of water vapour to the mass of dry air (w_0)	0.0098	Kilogram/ Kilogram
Ultimate ratio of mass of water vapour to the mass of dry air (we)	0.02	Kilogram/ Kilogram
Heat content at surrounding conditions (k)	52.2	Kilojoules/ Kilogram
Heat content at resultant conditions *(h_i)*	119.78	Kilojoules/ Kilogram
Dehydration period *(ta)*	12	Hours
Mean dehydration speed	0.15	Kilogram/ Hour
Amount of flow required to desiccate (m)	14.47	Kilogram/ Hour
Operational performance *(w)*	0.5	
Overall latent heat of vaporization *(L_o)*	11.73	Kilojoules
Yearly mean irradiance on shiny surfaces (I_{aw})	940	Joules/ Second -m^2
Yearly mean irradiance on shiny surfaces (I_{aw})	6.32	Kilojoules/ Hour -m^2

2.4. Sample Preparation

2.4.1. Solanoideae Family Produces

The Solanaceae family, commonly referred to as nightshades, is an important botanical family with substantial commercial significance. The greatest density of variety is observed in South America, where it is believed that this vegetable originates. Solanoideae is a subfamily of the flowering plant family Solanaceae and is phylogenetically associated with the subfamily Nicotianoideae. Solanoideae, a subfamily of Solanaceae, includes several economically important genera and species, such as tomato, potato, eggplant, chili, bell pepper, mandrake, and Jimson weed. Capsicum L. includes approximately 32 species, but, with the ongoing discovery of new species, the total is anticipated to exceed 40 in the forthcoming years. A significant amount of commercially valuable agricultural products is found in around thirty species of domesticated plants within the Solanum family.

2.4.2. Preparations

The selection of the vegetables is due to their easy availability and is preferred in the local market. Fresh vegetables (Chilli, Potato, Tomato, and Eggplant) were collected from local markets during May–June 2024 to ensure seasonal suitability and local availability. After collection, they were separated from plant material and thoroughly washed to remove dust and other impurities. The vegetables are sliced as per the recommendations by other authors in their research papers, and then soaked in the salt water to prevent them from discoloration.

3. Experimental Setup

The solar dryer consisted of two main components: a sun thermal receiver (Figure 1) and a dehydrating compartment, made to protect samples from incoming sunrays while maintaining characteristics (Figure 2). The frames were made from steel, fitted with aluminum receiver sheets covered with black color to improve thermal collection. PE foam was used as insulation, and inclined glass panels at a 30° angle enabled effective collection of sun radiation (Figure 2). The dehydrating compartment has 3 rows with an exhaust duct to remove moist air. Temperature and humidity were continuously recorded with 2 data collectors (Eli. G.-6). The system primarily includes a solar collector, a drying chamber, and an auxiliary heating element (used in hybrid dryers).

3.1. Solar Collector

The actual arrangement of the solar dryer is seen in Figure 3. The dryer has a solar collector with a glass covering of 4 mm thickness, as shown in Figure 4. The inside box of the solar collector is painted with black color (95% color + 5% black chromium powder) to maximize solar energy absorption, as shown in Figure 2. For the purpose of insulation, a 5mm thick rock wool covering is provided with a thermal conductivity of 0.04 $Wm^{-1} K^{-1}$.

3.2. Drying Chamber

The drying chamber (Figure 2) consists of three trays of size 0.6 x 0.48x 0.08 m and a square hole through which the chamber passes that carries flue gases from the burning of biomass. The trays are placed one above the other at a distance of 0.8 m.

3.3. Biomass Burner

A biomass burner with the facility to control heat flow with the help of an in-built fan is used to provide heat in case of insufficient supply from solar drying.

The use of biomass in the hybrid dryer is dependent on the atmospheric conditions. Various types of biomass can be used in the burner, viz., crop wastes such as rice husk, sawdust, wood chips, dried dung cake, leaves, twigs, bark, etc. In the present study, sawdust and wood chips are mainly used along with dried dung cake. Around 1 kg of biomass was used in the study. A simple biomass burner with an inbuilt fan to regulate the heat flow is used in the study. The biomass burner has a unique ability to burn any type of biomass, making it usable for a wide variety of fuels.

Fig. 1 Solar collector

Fig. 2 Drying chamber

3.4. Operation of the Dryer

The hybrid dryer was fabricated for working in such a way that the main source of energy is solar energy, and heat from biomass burning will be provided only when solar energy is unavailable, like early morning, evening, or during cloudy weather. The temperature inside the dryer cabinet is increased because of solar radiation that enters through the glass covering.

This heat is assimilated by the item kept to be dehydrated inside the chamber. This causes a change in temperature of the interior and exterior of the container. The heated flow through the inside of the dryer compartment absorbs the water and goes in an upward direction and goes out through the exhaust, which is present at the top of the chamber. This causes a pressure drop inside the chamber, and atmospheric air enters the cabinet. This causes a continuous supply of air. In case of scarcity or absence of solar energy, a biomass burner (stove) provides backup heating.

The flue gases from the stove go through the passage provided inside the drying chamber, which raises the temperature. The hot air rises inside the chamber, which evaporates and collects water content in the onion when air moves between compartments, and it leaves through the chimney. The temperature inside the drying chamber is maintained with the help of a fan in the stove.

The drying chamber consists of 3 trays, each of which is loaded with 1000 gms of vegetables. The hot flow through a collector and from the biomass burner passed through each tube, and then it was released to the atmosphere through the chimney, which is situated at the top of the dryer.

The various factors that are measured in this study include (i) initial and final weight and moisture present in the onion, (ii) solar radiation, and (iii) ambient humidity and humidity in the different parts of the dryer.

4. Observation

The water content in the vegetables was tracked by regularly weighing them during the drying process. At the same intervals, the air temperature inside the dryer was also monitored. Drying continued until the samples no longer lost moisture, indicating that equilibrium had been reached as per the dryer specifications.

Table 10. Time, Temperature, Radiation, Mass flow Rate of air variation with respect to time

SR. NO.	TIME	TEMPERATURE (◦C)							RADIATION (w/m²)	MASSFLOW RATE (m/s)
		T1	T2	T3	T4	T5	T6	T7		
16/04/2025 (DAY1)										
1	11:00	49	55	48	51	42	39	37	850	2.4
2	12:00	38	39	53	52	33	39	43	892	2.0
3	1:00	44	43	53	50	39	43	45	916	1.8
4	2:00	47	44	45	51	39	42	44	866	2.1
5	3:00	48	44	47	50	40	43	44	710	1.5
6	4:00	43	42	44	41	40	42	44	257	2.0
7	5:00	42	39	42	41	39	41	43	225	2.4
17/04/2025 (DAY2)										
8	10:30	51	43	46	42	36	38	39	804	2.1
9	11:30	53	57	56	55	41	42	43	913	2.0
10	12:30	59	64	59	53	45	48	47	926	2.5
11	1:30	63	57	61	58	45	49	50	860	2.3
12	2:30	62	57	61	48	45	45	47	688	2.1
13	3:30	56	52	54	49	43	46	47	540	2.3
14	4:30	50	51	47	46	45	46	47	282	1.9
18/04/2025 (DAY3)										
15	10:45	63	61	51	53	39	45	45	856	2.1
16	11:45	64	61	54	60	42	45	46	914	2.3
17	12:45	61	61	50	59	45	46	48	950	2.0
18	1:45	55	57	54	50	45	43	45	933	1.9
19	2:45	54	57	54	52	45	44	44	896	2.3
20	3:45	55	53	53	54	44	42	43	750	2.4

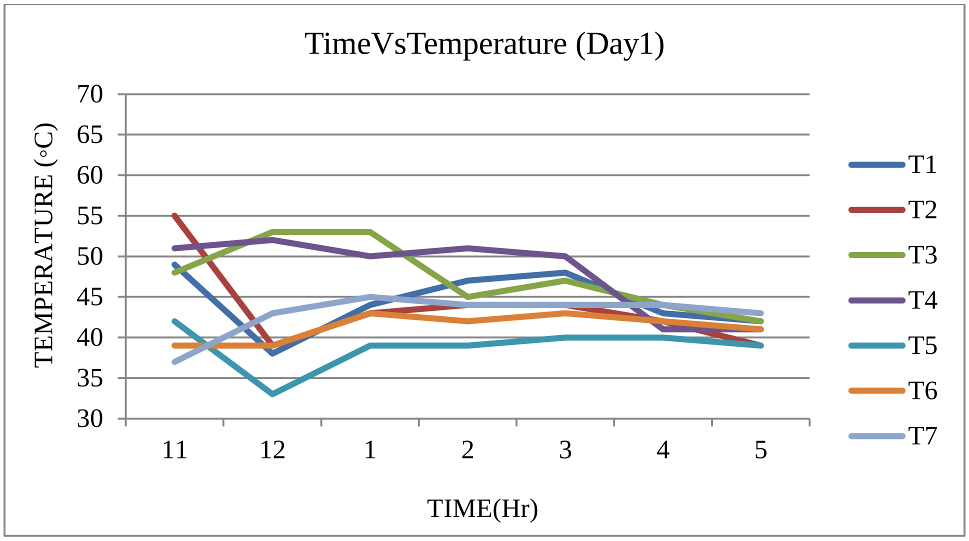

Fig. 3 Time Vs Temperature graph (Day 1)

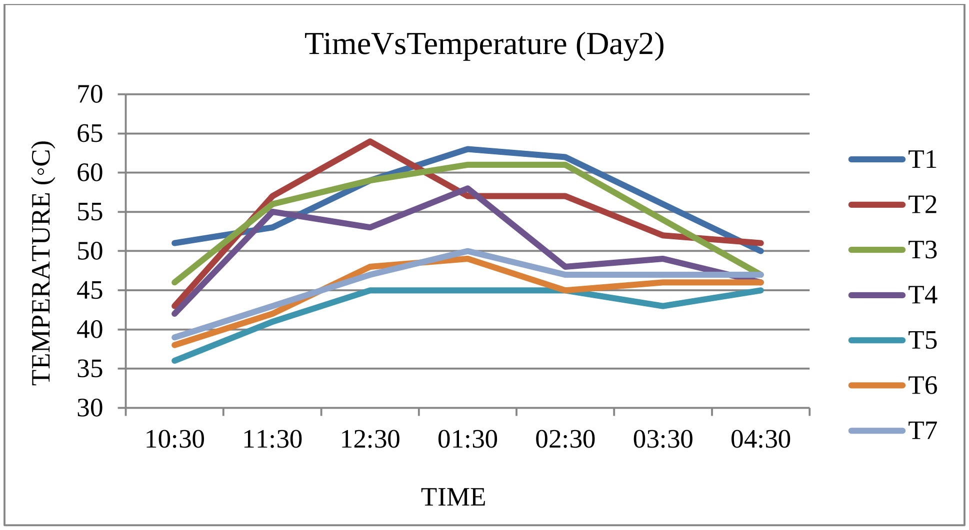

Fig. 4 Time Vs Temperature graph (Day 2)

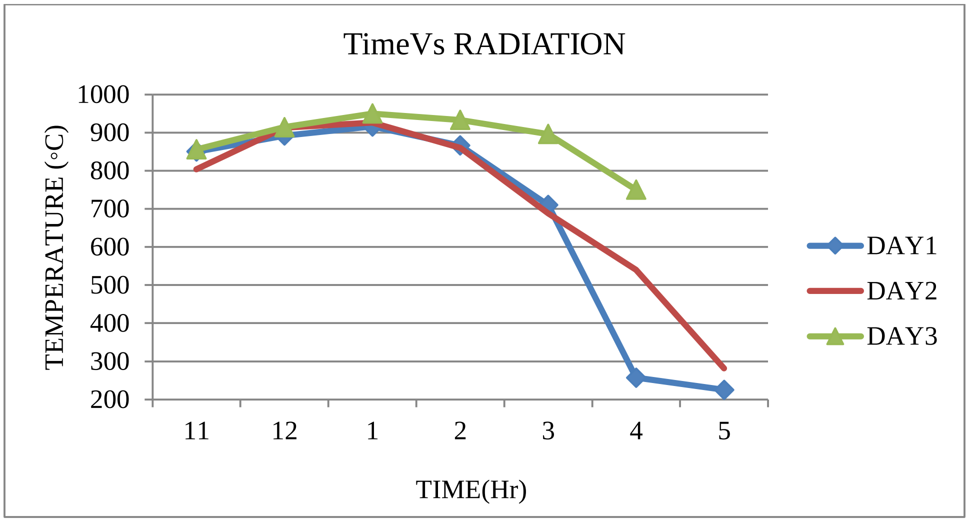

Fig. 5 Time Vs Temperature graph(Day 3)

Table 11. Variations in ML, Mwb, and DR with respect to time

SR. NO.	TIME	ML (g)			Mwb (%)			DR (g/sec)		
		Onion	Potato	Eggplant	Onion	Potato	Eggplant	Onion	Potato	Eggplant
16/04/2024(DAY1)										
1	11:00	-	-	-	-	-	-	-	-	-
2	12:00	300	470	308	0.30	0.47	0.31	11.67	7.83	11.53
3	1:00	433	510	584	0.43	0.51	0.58	2.21	0.67	4.60
4	2:00	540	565	674	0.54	0.57	0.67	1.78	0.92	1.50
5	3:00	582	586	785	0.58	0.59	0.79	0.70	0.35	0.35
6	4:00	633	600	803	0.63	0.60	0.80	0.85	0.23	0.12
7	5:00	642	638	810	0.64	0.64	0.81	0.15	0.63	0.88
17/04/2024(DAY2)										
8	10:30	745	700	863	0.74	0.70	0.86	1.71	1.03	0.05
9	11:30	764	728	866	0.76	0.73	0.87	0.31	0.47	0.13
10	12:30	784	767	874	0.78	0.77	0.87	0.33	0.65	0.00
11	1:30	800	801	874	0.80	0.80	0.87	0.27	0.57	0.00
12	2:30	808	833	874	0.81	0.83	0.87	0.13	0.53	0.00
13	3:30	819	850	874	0.82	0.85	0.87	0.18	0.28	0.00
14	4:30	829	859	878	0.83	0.86	0.88	0.17	0.15	0.07
18/04/2024(DAY3)										
15	10:45	849	878	878	0.85	0.88	0.88	0.33	0.35	0.00
16	11:45	855	885	878	0.86	0.89	0.88	0.10	0.12	0.00
17	12:45	856	887	879	0.86	0.89	0.88	0.02	0.03	0.02
18	1:45	860	887	879	0.86	0.89	0.88	0.07	0.00	0.00
19	2:45	860	887	879	0.86	0.89	0.88	0.00	0.00	0.00
20	3:45	860	887	879	0.86	0.89	0.88	0.00	0.00	0.00

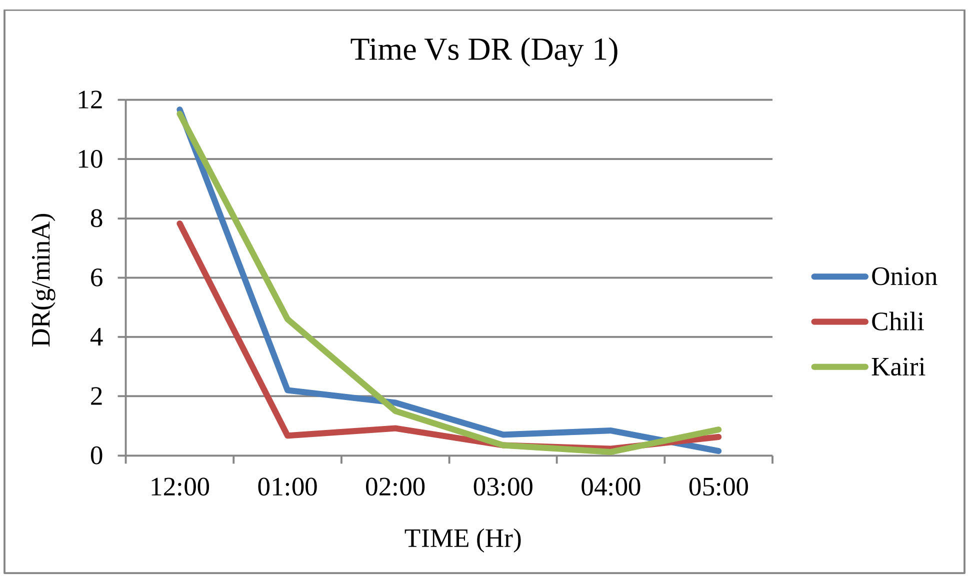

Fig. 6 Time Vs DR (Day 1)

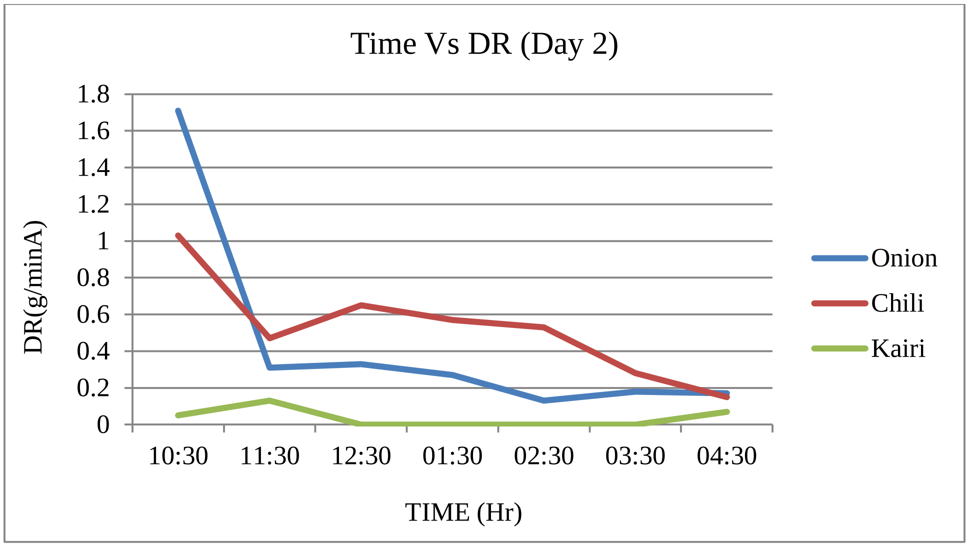

Fig. 7 Time Vs DR (Day 2)

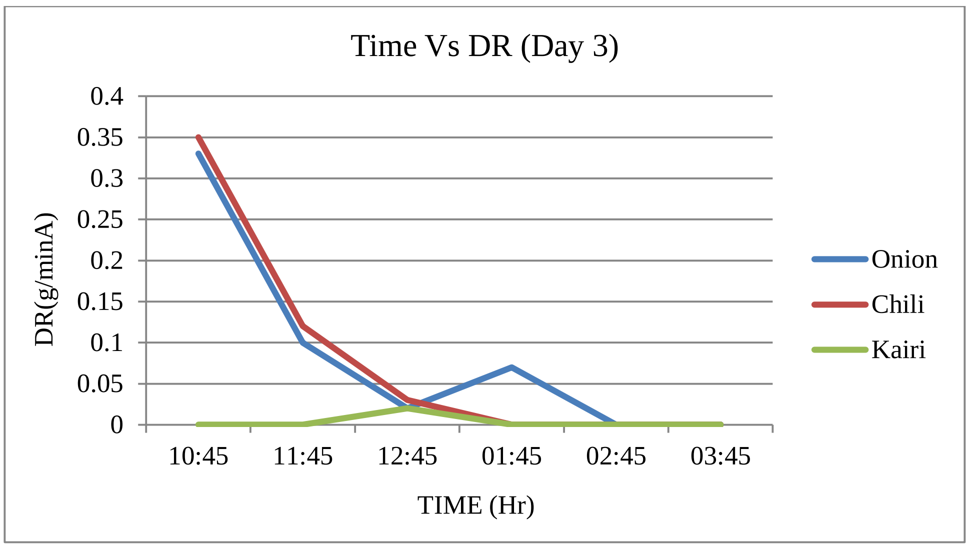

Fig. 8 Time Vs DR (Day 3)

The results show that the developed system has the ability to easily reach the required drying temperature with minimum resources and day-long working (in the absence of solar radiation). It is observed that Open Sun Drying and simple solar dryers do not possess these abilities. And this gives the hybrid solar dryer an edge over the conventional dryers.

5. Results and Discussions

The solar-biomass hybrid system showed regular and reliable performance through the three-day investigational phase. The changes in temperature and moisture removal registered during the experiments are summarized as follows:

5.1. Temperature Profile

The hybrid dryer again and again marked higher temperatures in the range of 60–65 °C, which is sufficient for efficient dehydration of vegetables. The average drying temperature in all experiments was 52.6 °C ± 4.1 °C, which shows steady performance in the best possible range for convective solar drying systems. A steady drop off in chamber temperature was observed after 13:00 h, subsequent to the natural decline in solar radiation strength observed during the afternoon period.

5.2. Drying Rate (DR) and Moisture Loss (ML)

In the first two hours of drying, the rate of drying was reasonably high due to the fast evaporation of outside moisture (e.g., 11.67 g/s for onion and 11.53 g/s for eggplant). During further drying, the speed of moisture elimination declined with the removal of bound moisture, which was consistent with the quality performance suggested by the Page drying model. On the third drying day, the moisture ratio (Mwb) reduced to the range of 0.86–0.89 for all samples. Statistical regression analysis gave a coefficient of determination (R^2) of roughly

0.82 between chamber temperature and drying rate, suggesting a strong reliance of drying kinetics on thermal conditions.

5.3. Comparative Analysis

On comparing the solar biomass hybrid system with open-sun drying, which requires 30 to 40 hours to dry the product up to a similar level of moisture reduction, the hybrid dryer requires a drying time of 18 to 20 hours, which means a reduction of nearly 45 % in drying time. The presence of a biomass auxiliary system helped to ensure continuous drying during non-solar periods, which increases the efficiency of the system by approximately 25 %.

The experiments showed that the solar dryer reached its peak temperature of about 60–65 °C between 12:00 and 13:00, after which the temperature gradually declined as solar radiation decreased. At the start of drying, the samples lost weight quickly due to surface moisture evaporating. With higher airflow, the moisture ratio dropped faster, which helped shorten the drying time. During sunny hours, the dryer maintained a mean temp. of 45–55 °C. Compared to open-air drying, the solar dryer required less time, worked more efficiently, and better preserved the product's color, taste, and nutrients. The addition of thermal energy storage allowed drying to continue at night when solar radiation was absent, further reducing the total daytime required for drying.

6. Conclusion

The findings showed that in just 12 hours, an initial moisture content in the food material fell to 5.5% (wb), while whole samples reached about 6.36% (wb). By comparison, open sun drying took around 25.5 hours to achieve similar results; on the other hand, conventional solar dryers also require a time span of 16 hours. Also, this hybrid dryer is capable of working in any season and at any time of the day with a constant heat supply, resulting in uniform drying characteristics of the products. The drying rate was fastest at the beginning, when moisture levels were high, especially in sliced samples. During isothermal drying, relative humidity tended to rise as the temperature decreased. The drying pattern also depended on the product's texture, with clear differences between sliced and whole samples. Overall, the solar dryer achieved about 30% thermal efficiency for chili drying and, importantly, helped prevent fungal growth in sliced samples—a problem often faced in humid regions with traditional sun drying.

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