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Thermal and Drying Efficiency Evaluation of a Solar-Biomass Hybrid System for Solanoideae family crops

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Abstract
This study presents the design, construction, and evaluation of an indirect hybrid solar-biomass dryer tailored for post-harvest processing of Solanoideae family vegetables, including eggplant, capsicum, and tomato. Traditional solar drying techniques suffer from inconsistencies due to weather dependence, contamination risks, and limited nighttime functionality. To address these issues, a hybrid dryer was developed incorporating a solar flat plate collector and a biomass-fired heat exchanger to enable continuous drying, even during low solar irradiance periods. The system includes three meshed aluminum trays in a thermally insulated chamber and utilizes forced airflow driven by natural convection and biomass combustion. Experimental trials conducted in Amravati, Maharashtra, demonstrated that the system successfully reduced crop moisture content from initial levels to 8–10% (w.b.), with observed drying efficiencies of 19.65% and stable chamber temperatures. The hybrid design minimized rehydration risk, maintained product quality, and allowed efficient energy utilization. The findings highlight the system's potential for reducing post-harvest losses in rural and off-grid regions, with implications for scalable deployment in developing countries to enhance food security and farmer income.
Keywords: *Solar Dryer, Hybrid Dryer, Solar Energy, Solanoideae family crops.*

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I. Introduction

Moisture removal is the process of decreasing Moisture Content (Mc) up to a tolerable level. Solar drying is a proven technique employed globally for ensuring the longevity of crops. Solar drying is an efficient technique for using energy from the sun. [1] Solar drying refers to the prolonged contact of a product to naked direct 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. [2] The dried produce is able to 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. [3]

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. [4] These types of dryers not just diminish the duration of drying but additionally enhance the overall quality, colour, and flavour of the items that are dried. [5]

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 air. The warmth is introduced into a container carrying food produce. The food items undergo heating to reduce their level of moisture. [6] 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 solar rays through mansoon or overcast days and it is absent at nighttime. In a hybrid 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. [7,8] 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. [9] The combination of a heat energy storage with solar energy is beneficial because of the periodic characteristics and daily fluctuations of solar power. [10]

The workings of a solar assisted drier 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 re-hydration by the surroundings. [11,12,13] Jha et al. [14] examined the importance of hybrid solar-powered dryers in relation to the capacity to endure diverse atmospheric and uncontrollable environment circumstances, as well as their influence on the drying properties of food items. The evaluation indicated that heat exchanger hybrid solar dryers were highly effective, offered a broad spectrum of drying conditions, and were appropriate for thermal-sensitive items. Some of the benefits of biofuel hybrid solar dryers include their capacity to utilise inexpensive neighborhood assets to meet energy needs.

The major disadvantages associated with solar dryers include higher initial Costs which include fabrication cost, complexity in design due to simultaneous use of both solar and biomass energy, space requirements, maintenance, and energy efficiency. These potential disadvantages should be considered when evaluating the suitability of the hybrid solar-biomass dryer for specific applications and environments. [15]

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 [16] or using pv-solar integrated system [17]. Abishek Ganesh's [18] study on phase change material-based thermal storage systems for sun 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%, correspondingly. Ehsan Baniasadi [19] conducted an experimental analysis of the efficiency of a forced convection dryer that included thermal energy 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 okra were diminished to ultimate moisture contents of 0.01 and 0.12 kg/kg on a dry basis, correspondingly, from beginning moisture contents of 8.3 and 10.1 kg/kg on a dry basis. The solar air collectors effectiveness and effectiveness of drying for Capsicum were 74.13% and 9.15%, correspondingly, whereas for okra, they were 78.30% and 26.06%, correspondingly.

[20] Mostafa M. Azam designed an autonomous hybrid solar greenhouse drier (GD) incorporating a photovoltaic technology and solar collectors for small tomato processor after harvesting. [21] Assess the thermal efficiency of forced convection gas diffusion via a modeling approach. Examine several preparatory steps on freshly picked tomato prior to drying, determine the optimal process, and assess the nutritional value of the end result in comparison to open sun drying.

Numerous research have documented the modeling of forced convective solar drying of agriculture items across different kinds of force convective solar dryers. [21, 22]

The research conducted by Samira Chouicha [23] 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 drying of chopped potatoes through heated convection in an drier, utilizing supplementary energy from a heater powered by the Joule effect, which is provided by parallel-connected photovoltaic 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 [24] engineered, fabricated, and operated a compact solar drier for the drying of chopped onions. The primary parts of the dryer consisted of 2 collectors, a dehydrating system, and an airflow-handling system. The drying period average 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.

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 drying air temperature throughout the period of drying, which is influenced by fluctuations in solar intensity throughout sunlight hours. The efficacy of the current solar dryers is inadequate and requires enhancement.

The aim of the present research was to design continually evaluate a hybrid solar dryer (operating daytime and at night) by supplying heat energy via a biomass burner during night hours to reduce drying costs, enhance the quality of dried items, and inhibit mould development through the drying process.

II. Materials and methods

2.1 Solanoideae family produce

The Solanaceae family, also known as nightshades, is a significant botanical family with considerable commercial relevance. The highest density of variation is seen in Southern America, where it is thought that this vegetables originates. Solanoideae is a subgroup within the group of flowering plants called Solanaceae and is phylogenetically related to the subgroup Nicotianoideae. Solanoideae, a subfamily of Solanaceae, encompasses several financially significant genus and species, including Tomato, Potato, Eggplant, Chilli and Bell Peppers, Mandrakes, and Jimson Weed. [25] Capsicum L. comprises roughly 32 species[26]; but, due to the continual identification of fresh species, the total is expected to surpass 40 in the coming years. A substantial quantity of commercially important agricultural produce exists across approximately thirty varieties of domesticated plants within the family Solanum[25].

2.2 Design of indirect hybrid dryer

The conventional biomass-fired rapid drying technology adversely impacts the colouration of the finished dehydrated commodity. A passive technique of drying is essential to preserve the colour as well as quality throughout the drying process. The constructed unit comprises solar collectors, a passive warm air generation structure utilising biomass, featuring a biomass burner, a solar collector, and a drying area (chamber)[26]. The solar collector's outer shell of is 2 m × 1 m and consists of a 4 mm thick glass plate. The collector plate is 2 m × 1 m and is constructed from an aluminum sheet having a dark finish. The solar powered collector with flat plate was lined with 10 mm thick polyurethane sheet and externally clad with galvalume plate to safeguard it against rainfall and other environmental triggers.

The chamber used for drying has three wire-meshed aluminum trays, each measuring 1 m × 1 m, which is shielded with PUF and coated with an aluminum to endure any type of weather. The solar flat plate collector was subsequently enclosed with galvanised plate to safeguard it from precipitation and various environmental conditions. The metallic conduit was utilized for transporting heated air generated by the flat-plate collector to the dryer area.

The drying compartment encompasses three meshed aluminum trays, each measuring 0.7 m × 0.7 m, and is completed with a mild steel sheet to endure different climate conditions. The system developed for transforming the heat from biomass burner to the drying chamber is comprises of two main parts. The initial chamber serves as the burner for incinerating biomass or agricultural leftovers. Then following section is the hot-gas to air heat exchanger, comprising an metal pipe for transferring warmth between a hot-flue gases and ambient air. The hot gas traverses the pipe for exchange of heat with the natural draft facilitated by a chimney-pipe, while fresh air circulates through the passageways of the heat exchanger in a crossflow configuration.

In the heat exchanger, thermal energy from the heated flue gas is conveyed to the incoming fresh air. The heated air generated by a biomass air warming system is directed into the drying chamber to enable the continued dehydration of vegetables during non-sunny periods, such as nighttime or overcast conditions. Table 1 presents the specifications of the constructed solar-biomass hybrid dryer.

Table 1
Specifications of a dryer

Sr. No.	Part details	Features of material	Characteristics
1	**Collector plate**		
	Area	2 m^2	
	Transparent Cover	Glass	4 mm
	Absorber plate	Galvanized Iron with black coating	1 mm
	Distribution duct	Galvanized Iron	1 mm
2	**Area of chamber for drying**		
	Area	Aluminium sheet	1m x 1m
	Trays	Aluminium perforated sheet	Length = 0.7 m Width = 0.7 m Mesh size = 3 mm
3	**Biomass Heating System**		
	Combustion Chamber	M. S. Sheet	Volume = 0.05m^3 Area = 0.1m^3 Diameter = 0.18 m
	Heat Exchanger	Electric Resistance Welded (ERW) Pipe	Area = 0.66 m
	Chimney	Galvanized Iron	1 mm

III. Experimental investigation and apparatus

The study was done from May 28 to June 2, 2024, between 6:00 AM and 6:00 PM, in the meteorological circumstances of Amravati, Maharashtra. Samples of locally picked crops weighing 2 kg were placed in the trays at 6 A.M., and the process lasted until the final moisture content reached 8 to 10% (w.b.). The Solar Biomass Hybrid Dryer utilised solar energy for dehydrating Solanoideae family crops, such as freshly produced Brinjal, Pepper, and Tomato, till 6:00 PM, supplemented by a biomass-based indirect hot air generation system as needed. During the utilisation of biomass mode, a biomass-based indirect hot air generation system was employed throughout the drying process to ensure uninterrupted drying. Figure 1 illustrates the dryer utilised for drying purposes.

Fig. 1 Solar Biomass Hybrid Dryer

The temperature was measured using the K- Type Thermocouple with temperature indicator. A K-type thermocouple is a commonly utilised base metal thermocouple composed of Chromel (a Nickel-Chromium alloy) and Alumel (a Nickel-Aluminium alloy). It is recognised for its versatility, extensive temperature range, and excellent oxidation resistance. Type K thermocouples function based on the Seebeck effect, wherein a temperature differential between two distinct metal junctions produces a voltage. The voltage is directly proportional to the temperature differential and can be quantified to ascertain the temperature of the object being examined. The important data like solar flux(irradiance), temperature and humidity, etc is accessed through the POWER project run by NASA.

3.1 Moisture content and moisture ratio

Moisture ratio is a dimensionless value representing the ratio of the moisture content of a material at any given time to its initial moisture content. It's a key concept in drying processes and helps track the progress of moisture removal. Consequently, the initial and final moisture levels are computed with Eqs. 1 & 2. [27]

$$Mo = \frac{Wo-Wd}{Wd} \quad (1)$$

$$Mf = \frac{Ww-Wd}{Wd} \quad (2)$$

The moisture ratio was computed as follows:

$$\mathrm{MR} = \frac{\mathrm{M-Me}}{\mathrm{Mo-Me}} \quad (3)$$

Nevertheless, for a sun drier process characterised by variable relative moisture and an extended drier duration, the formula could be simplified to,

$$\mathrm{MR} = \frac{\mathrm{M}}{\mathrm{Mo}} \quad (4)$$

3.2 Drying Efficiency

Drying efficiency refers to how effectively a dryer utilizes its input energy to remove moisture from a material. It's a measure of how much energy is actually used for evaporation, compared to the total energy provided to the dryer. The comprehensive drying effectiveness of solar hybrid dryer could be calculated using the subsequent equations[28].

For Biomass mode,

$$\eta s = \frac{W \times L}{(mb \times CV)} \quad (5)$$

For Hybrid Mode,

$$\eta s = \frac{W \times L}{(IA + pf) + (mb \times CV)} \quad (6)$$

IV. Result & Discussion

At the conclusion of the investigation, 1060 grammes of sliced Eggplant were dehydrated to a final weight of 76 grammes and that of Capsicum was reduced from 1050 grammes to 116 grammes. The dried samples of the vegetables are shown in Fig. 2.

Fig. 2. Dehydrated vegetables

The final moisture level was found to be 7.13% to 11.43% (equation 4). The overall solar energy irradiation on the collector's surface during air drying was measured at 11305 kJ, and converted to standard energy units of 3.14 kWh. The operational effectiveness of the solar collector was determined to be 19.65%, whereas the average irradiance measured was 639 W/m².

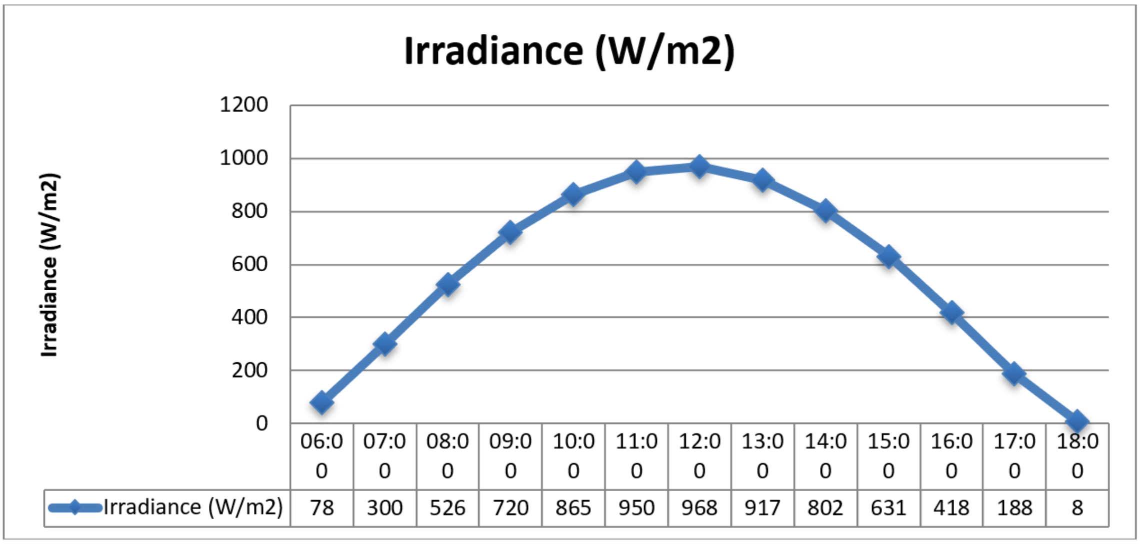

Fig. 3 Time vs irradiance

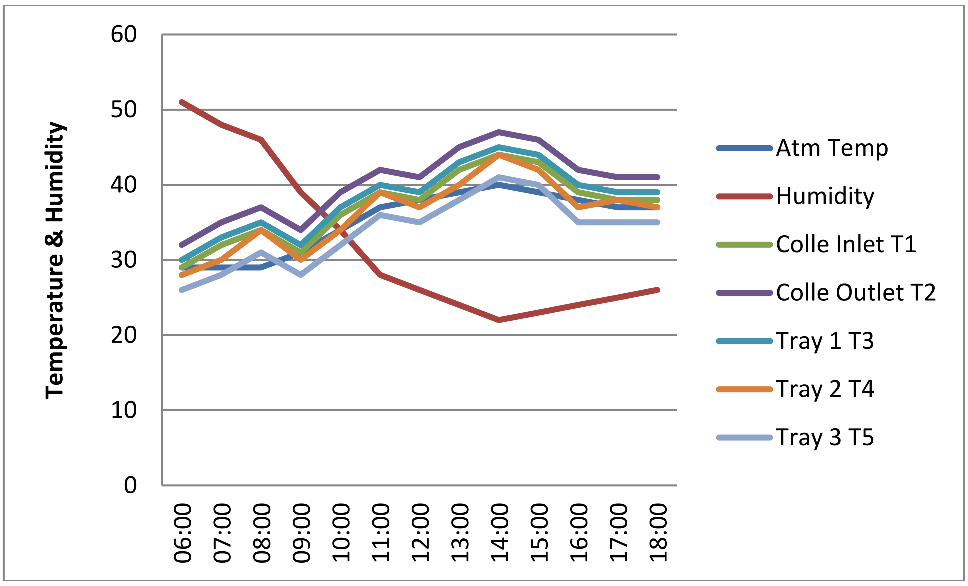

Fig.4 Temperatures, relative humidity vs time

The relative humidity of the ambient air going into the dryer appears to remain steady during the initial moment of the study, whereas the water content of an airflow exiting the drying space consistently declines until approximately 14:20 hours. This may suggest that the majority of the moisture via the final item was diminished by that time, despite a concurrent decrease in irradiance. At reduced moisture content, the heat duty necessary for moisture evaporation is much elevated, rendering temperature effects negligible at this point.

The air temperature exiting the dryer (T2) had observed as elevated relative to the temperature of the heat coming into the collector (T1). It outcome contradicted expectations, prompting the authors to recognise this is attributable to the chimney that was designed to be positioned at the initial exit point of air from the drying chamber, thereby being in close relation to the data collector.Humidity was observed to diminish with rising eat, as shown by the air entering the collector and exiting into the drying chamber.

The standard deviation of humidity levels was significantly higher at the drying chamber outflow than at the entrance, likely due to fluctuations in the speed of dehydration of the product as the amount of water diminishes.

The dehydrated vegetables exhibited favorable flavour, pleasing texture, and vibrant colour; they are convenient to consume and do not possess the excessive moisture linked to fresh vegetables, which may stain clothing or dampen the body.

V. Conclusion

The results demonstrated superior total effectiveness despite a greater amount of dryer batches relative to the originally intended batch size. This may be ascribed to the trays design covering the chamber for drying, effective air flow distribution, superior chimney efficiency, and a greater mean irradiance (567 W/m2) relative to the planned mean irradiation (500 W/m2).

It was beneficial in ascertaining humidity ratios, hence indicating variations in humidity ratio among the dehydration chamber's input and output. By analysing the ratios of humidity and dew point values measured at the entrance and exit of the drying chamber, together with the temperatures, it is determined that the space can enhance its effectiveness by upwardly accommodating an additional drier tray stack.

This investigation indicates that a dryer, with the same design, necessitates a collection area of 1 m^2 to dehydrate three kilogrammes of sliced vegetables from a level of 86% to 8.12% during 9 hours, under an average irradiance of 534.4 W/m^2. This indicates a collector area of roughly 32 m^2 to dry a batch of 50 kilogrammes to the same moisture content within 9 hours, and a collector area of approximately 30 m^2 to reduce 50 kg from a moisture content of 86% to the minimum needed moisture content of 15%, with potential advantages of economies of scale.

The large-scale replication of this design in mid-latitude locations can alleviate post-harvest losses, particularly in poor nations, thereby enhancing food security and yielding greater profits for farmers. This layout may pose challenges for massive system implementation, as the dryer may necessitate a specialised design for the angle of elevation change system of the collection because of its improved size and mass. The flow of air in a natural convection sun dryer can't be maintained consistently. Consequently, it may be impractical to ascertain when the material will be fully dried, particularly in regions with fluctuating hourly weather conditions.

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