

Design, Development and Performance Evaluation of Even Span Roof Structure Chimney Assisted Green House Solar Dryer for Agricultural Produce

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Abstract

This study focuses on the design, development, and performance evaluation of chimney-assisted greenhouse solar dryers: even-span, type, developed for drying wheat and paddy. The designs were fabricated based on key engineering and environmental considerations. Drying trials were conducted using 15 kg of wheat and paddy. Experiments were carried out for one day during both winter and summer seasons using the even-span design, with an 8-hour drying period each day. Ambient data were recorded using a weather station at AKS University, Satna, Madhya Pradesh, India, and validated with instruments such as anemometers, digital hygrometers, thermometers, and lux meters. The key parameters monitored included ambient temperature (°C), solar irradiance (W/m²), relative humidity (%), dryer temperature (°C), thermal efficiency (%), drying duration, and final moisture content (% wet basis). Dryer performance was evaluated based on thermal efficiency and temperature rise relative to ambient conditions. The maximum internal temperature recorded was 56.5°C in April 2022 for wheat drying and 34.4°C in December 2022 for paddy drying. The temperature inside the dryer exceeded ambient conditions by 16°C in April and 13.6°C in December. Moisture content of wheat decreased from 17.6% to 14.2%, while that of paddy reduced from 18.5% to 15.0% over an 8-hour drying period. The thermal efficiency was found to be 10.25% for wheat and 13.5% for paddy, indicating effective utilization of solar energy for drying these crops.

Keyword: Design of Solar dryer, Solar drying, Greenhouse dryer, Thermal efficiency of dryer, Design of solar dryer for wheat and Paddy drying

Introduction

Background, Post-Harvest Losses, and Research Significance

Agriculture is one of humanity's oldest and most vital activities, providing the foundation for food security and economic development worldwide. India, as an agriculture-dominant country, cultivates a wide range of crops, including cereals, pulses, oilseeds, spices, plantation crops, and horticultural products (FAO, 2024). Global crop production reached 9.6 billion metric tonnes in 2022, with cereals accounting for the largest share at 33.3%, followed by sugar crops (23%), vegetables (12%), oilseeds (12%), fruits (10%), and roots and tubers (9%). In India, the Ministry of Agriculture & Farmers Welfare (2023) reported total food grain production of 329.69 million tonnes in 2022–23, including 135.54 million tonnes of rice and 110.55 million tonnes of wheat, alongside substantial production of oilseeds, sugarcane, fruits, and vegetables. While these figures reflect increasing productivity, challenges persist, including reliance on water-intensive crops, regional productivity imbalances, and vulnerability to climate change.

A major concern in Indian agriculture is post-harvest losses (PHL), which remain significant despite increasing production. Food grain output has risen from 74.23 MMT in 1966–67 to 330.5 MMT in 2022–23, and horticultural production from 96.6 MMT in 1991–92 to 355.25 MMT in 2022–23. However, limited mechanization, inefficient storage, and poor logistics contribute to substantial losses, estimated at USD 18.5 billion annually (NABARD, 2022). A government survey across 54 commodities and 15 agro-climatic zones reported losses ranging from 3.9–5.9% in cereals, 5.7–6.7% in pulses, 2.9–7.5% in oilseeds, 6–15% in fruits, and 4.9–11.6% in vegetables, emphasizing the need for improved post-harvest management.

Drying is a traditional and effective method to reduce crop moisture content and minimize post-harvest losses. While open sun drying is widely practiced, it is prone to contamination, inconsistent moisture reduction, and quality deterioration. Mechanical dryers provide better control but are costly and energy-intensive, making them inaccessible to small and marginal farmers. Solar dryers have emerged as a sustainable, cost-effective alternative for crop drying in rural and remote areas. They harness solar energy to reduce moisture content while maintaining crop quality. Incorporating a chimney into greenhouse solar dryers enhances natural convection, improves airflow, and increases drying efficiency by raising internal temperatures through buoyancy-driven ventilation (Madhva et al., 2017). Given India's abundant solar resources and the increasing need for sustainable post-harvest technologies, the development of low-cost, efficient solar dryers is essential. Such systems can bridge the gap between crop production and safe storage, reduce post-harvest losses, improve food security, and provide economic benefits to smallholder farmers. This study focuses on the design, development, and evaluation of chimney-assisted greenhouse solar dryers for staple crops like wheat and paddy, aiming to optimize drying efficiency, preserve quality, and promote adoption among resource-constrained farmers. Drying is a critical process in post-harvest management, as it reduces the moisture content of agricultural produce to safe levels, thereby minimizing losses due to microbial growth, spoilage, and insect infestation. Wheat and paddy, being staple food crops worldwide, require efficient drying methods to ensure better storage stability and maintain quality. Although traditional open sun drying is widely practiced due to its low cost, it is highly dependent on weather conditions and prone to contamination, resulting in uneven drying and quality degradation. India, as a tropical country, receives abundant solar radiation, making it highly suitable for solar-based drying technologies. The average solar radiation in India ranges from 4 to 7 kWh/m² per day, with an annual total of 1200 to 2300 kWh/m². The country also experiences approximately 250–300 clear sunny days and 2300–3200 hours of sunshine annually (Sharma, N.K., 2018), indicating significant potential for solar energy utilization. Greenhouse solar dryers have emerged as effective alternative to traditional methods, as they provide protection from environmental contaminants while efficiently utilizing solar energy for drying. The addition of chimney assistance further enhances airflow and ventilation, thereby improving drying performance. However, existing studies primarily focus on large-scale systems or mixed crop drying, with limited research dedicated to small- and medium-scale dryers specifically designed for wheat and paddy. The temperature difference between the ambient environment and the dryer chamber

plays a vital role in effective solar energy utilization during drying. Thermal efficiency is an important parameter in evaluating solar drying systems, as it reflects how effectively solar energy is converted into useful heat, though it varies depending on the crop type. However, differences in design configurations, operating conditions, and measurement approaches often lead to inconsistencies in reported efficiency values. This study aims to evaluate and compare the drying performance, thermal efficiency, and economic feasibility of three chimney-assisted greenhouse solar dryer designs under both no-load and load conditions, with specific emphasis on wheat and paddy crops. Previous research highlights the effectiveness of solar drying systems in improving drying rates and product quality compared to conventional methods. For instance, Piwsaoad (2024) reported thermal efficiencies ranging from 24% to 27% for greenhouse solar dryers used in sticky rice drying. Kumar et al. (2023) reviewed optimization strategies for solar drying systems, emphasizing the need to balance technical performance with economic viability and environmental sustainability, along with considerations such as rural development and food security. A major challenge faced by marginal and small-scale farmers is the high cost associated with large-scale drying systems. Therefore, there is a pressing need to develop low-cost solar dryers suitable for low-moisture crops and adaptable to the Indian context. The present work addresses this need by focusing on affordable and efficient drying technology. Tawfik et al. (2023) developed a controlled natural convection solar greenhouse dryer for grapes using glass and Plexiglas covers. Their system, equipped with a photovoltaic control unit, reduced moisture content from 5.91 to 0.15 g/g within 12 hours and achieved a thermal efficiency of 12.5%, performing comparably to forced convection systems and outperforming conventional natural convection dryers. Similarly, Seetapong et al. (2017) evaluated a natural convection solar dryer under real weather conditions, reporting an average chamber temperature of 63.19°C, solar radiation of 759.53 W/m², and thermal efficiency of 2.59%. Furthermore, Nithya et al. (2011) investigated the effects of moisture content and storage temperature on durum wheat deterioration. Their findings indicated that higher moisture levels (16–20% wet basis) and temperatures (20–40°C) accelerate spoilage, reduce germination, and increase mould growth. They recommended maintaining moisture content below 15% and storage temperature below 20°C, along with timely drying of high-moisture grains within one week. While these guidelines are effective, their implementation in developing regions may pose practical challenges.

Brief Review on Design, Development and Thermal Performance, and Economic Evaluation of Solar Dryers

Recent studies highlight the growing importance of solar drying technologies in addressing global challenges such as food waste, energy consumption, and environmental sustainability. Fernandes et al. (2024) emphasized that nearly one-third of global food production (approximately 930 million tonnes annually) is lost across the supply chain, while a significant portion of the population faces malnutrition. At the same time, the food sector contributes substantially to greenhouse gas emissions. These concerns have accelerated the adoption of renewable energy solutions, particularly solar drying, as a sustainable alternative for food

preservation. Kherrafi et al. (2024) provided a comprehensive overview of solar drying technologies developed over the past decade, focusing on improving system efficiency, reducing drying time, and optimizing performance. Their study compared various dryer configurations and highlighted advancements such as hybrid systems, integration of thermal energy storage, and the use of computational tools like CFD modeling to enhance design and operational efficiency. Similarly, Venkateswarlu and Reddy (2024) reviewed modern approaches to improving energy efficiency in solar dryers. They addressed the variability of solar radiation and proposed solutions such as hybrid dryers, solar-assisted heat pumps, and systems incorporating desiccants and thermal energy storage, including phase change materials (PCMs). Key performance indicators such as drying temperature, energy and exergy efficiency, specific moisture extraction rate (SMER), and CO₂ mitigation potential were also discussed, along with economic feasibility and sustainability considerations. Experimental investigations have demonstrated significant improvements in drying performance through innovative designs. Sachithanandhan et al. (2024) developed an indirect solar dryer integrated with a wicked heat pipe system, achieving a temperature rise of 21°C above ambient and reducing banana moisture content from 150% to 11% (dry basis) within 12 hours. The system showed a thermal efficiency of 26% and a short payback period of 0.57 years, making it suitable for rural applications. Piwsaoad (2024) studied greenhouse solar dryers for large-scale sticky rice drying and reported thermal efficiencies ranging from 24% to 27%, with accurate moisture prediction using heat transfer modeling. Jain et al. (2023) introduced a solar conduction dryer enhanced with reflectors, achieving higher internal temperatures (up to 77.4°C under no-load conditions) and improved drying efficiency (59.4%). The system also demonstrated economic viability with a payback period of approximately one year. Srinivasan et al. (2021) presented a comprehensive review of solar greenhouse dryers, covering design configurations, thermal modeling, drying kinetics, and economic analysis. Their work also examined environmental impacts, including CO₂ mitigation and energy consumption, providing a holistic understanding of solar drying systems. To address the intermittency of solar radiation, Rulazi et al. (2023) developed a passive solar dryer with soapstone-based thermal energy storage, which significantly reduced drying time and achieved a thermal efficiency of 45%. The system also improved product quality and provided extended drying capability after sunset. In another study, Singh and Gaur (2021) developed a hybrid active greenhouse solar dryer integrated with an evacuated tube collector and heat exchanger. The system significantly reduced drying time for various crops and demonstrated improved energy efficiency and environmental benefits, including reduced CO₂ emissions and lower energy payback time. Overall, the reviewed literature indicates that advancements in solar dryer design, incorporation of thermal storage systems, hybridization, and modeling techniques have significantly improved drying efficiency, reduced energy consumption, and enhanced economic feasibility. However, there remains a need for cost-effective, small- to medium-scale solar dryers tailored to specific crops such as wheat and paddy, particularly for marginal and small farmers in developing countries.

Materials and Methods

Initial Moisture Content and Physical Properties of Wheat (Pusa Tejas Variety) and Paddy (Kala Namak Variety)

The physical properties of wheat and paddy grains, including size and bulk density, were measured using a measuring cylinder, digital vernier calipers, and a digital balance, as described in the Materials and Methods section. The recorded bulk density was 745 kg/m³ for wheat and 560 kg/m³ for paddy (Table 1). The initial moisture content was found to be 17.4% (wet basis) for wheat and 18.2% (wet basis) for paddy (Table 2). Grain dimensions were determined by measuring 10 randomly selected samples of each crop, and the average values were calculated. Wheat grains exhibited mean dimensions of 5.2 mm in length, 2.5 mm in breadth, and 2.2 mm in thickness. In comparison, paddy grains showed average dimensions of 8.0 mm in length, 3.2 mm in breadth, and 2.0 mm in thickness (Table 1). Sphericity values were also calculated for both grains using standard expressions. The maximum possible sphericity value is 1, representing a perfect sphere. The calculated sphericity was 0.58 for wheat and 0.46 for paddy, indicating that both grains are non-spherical but maintain relatively uniform geometric shapes compared to many other agricultural products.

Sr.No	Dimension	Unit	Dimension/Unit
1	Size ($l \times b \times t$)	(in mm)	Wheat (5.2 x 2.5x 2.2 mm) Paddy (8.0 x3.2x 2.0 mm)
2	Sphericity ($l \times b \times t$) ^{1/3} /l	Maximum Value is 1	Wheat (0.58) and Paddy (0.46)
3	Bulk Density of wheat and Paddy	Kg/m ³	Wheat (745 Kg/m ³) Paddy (560 Kg/m ³)

Table 1 Physical Properties of wheat and paddy

Sr.No.	Crop	Initial Moisture Content(%Wb)
1	Wheat	17.4
2	Paddy	18.2

Table 2 Initial Moisture Content of Wheat and Paddy

Fabrication of Chimney-Assisted Greenhouse Solar Dryers

Even Span Roof Structure Chimney-assisted greenhouse solar dryer was designed, fabricated, and tested in the workshop of the Department of Mechanical Engineering at AKS University, Satna (Madhya Pradesh), India. The objective was to evaluate their performance in terms of thermal efficiency, internal temperature, structural stability, material cost, and moisture reduction for wheat and paddy. The designs were developed by considering local climatic conditions of Satna, the characteristics of the selected crops, and the availability of construction materials. Key

design parameters were identified prior to fabrication to ensure optimal performance. The dryers were constructed using mild steel (MS) angles, MS pipes, and a 200-micron polythene sheet as the covering material.

Experimental Setup and Procedure

Drying experiments were conducted under natural ambient conditions during two different seasons: April 2022 for wheat and December 2022 for paddy. The objective was to evaluate the drying behavior and thermal efficiency of the developed dryer. Ambient weather parameters, including ambient temperature ($^{\circ}\text{C}$), solar irradiance (W/m^2), and relative humidity (%), were recorded at the beginning and end of drying periods between 09:00 AM and 5:00 PM. Measurements were taken using instruments such as a lux meter, anemometer, digital temperature and relative humidity meter, digital weighing balance, and a weather station installed at the AKS University campus. The dryer was tested to identify the internal temperature distribution, air circulation pattern, and overall thermal behavior. Full-load experiments were conducted using 15 kg of wheat and 15 kg of paddy, separately, during their respective harvesting seasons. The grains were uniformly spread inside the drying chamber. Data on ambient temperature, dryer temperature, relative humidity, and solar irradiance were recorded at regular intervals throughout the drying period. These experiments provided insights into moisture reduction patterns, drying characteristics, and thermal efficiency of the chimney-assisted greenhouse solar dryers.

Thermal Efficiency of Chimney-Assisted Greenhouse Solar Dryer

The thermal efficiency (η) of the chimney-assisted greenhouse solar dryer was determined as the ratio of useful energy utilized for moisture evaporation to the total solar energy input incident on the collector area. It was calculated using the following relation:

$$\text{Thermal Efficiency} = \text{Usefull energy} / \text{Total Input energy} \text{ (Saxena, A.et al.)}$$



Fig. 3. Fabricated Chimney-assisted greenhouse solar dryer designs for wheat and paddy drying at the Department of Mechanical Engineering, AKS University, Satna (Madhya Pradesh), India.

Results and Discussion

Thermal Efficiency of Chimney-Assisted Greenhouse Solar Dryer

The experimental results revealed that the Even Span design of the chimney-assisted greenhouse solar dryer achieved significantly higher drying chamber temperatures compared to ambient conditions, thereby enhancing the moisture removal rate for both wheat and paddy. The maximum temperature inside the dryer was observed to be 13.6°C higher than the ambient temperature. The thermal efficiency of the dryer was calculated as 10.25% for wheat and 13.5% for paddy. A noticeable reduction in moisture content was achieved during the 8-hour drying period, with paddy moisture decreasing from 18.5% to 15% (wet basis), and wheat moisture reducing from 17.6% to 14.2% (wet basis). These results demonstrate the effectiveness of the dryer in improving drying performance under controlled conditions.

Effect of Ambient Conditions on Chimney-Assisted Greenhouse Solar Dryer

For loaded experiments, 15 kg batches of wheat and paddy with known initial moisture content were placed inside the dryer during summer and winter seasons, respectively. Moisture reduction was monitored at regular intervals and Initial moisture content of crop were calculated as per the standard method using on wet basis. The internal temperature of the dryer was continuously recorded using digital thermometers installed at different locations within the drying chamber. During paddy drying, the maximum and minimum temperatures recorded inside the dryer were 34.4°C and 23.8°C, respectively. For wheat drying, the corresponding maximum and minimum temperatures were 56.6°C and 23.6°C. The temperature difference between ambient air and the dryer chamber reached up to 16°C during wheat drying and 12.2°C during paddy drying. These temperature variations indicate that ambient conditions significantly influence the thermal performance and drying efficiency of the chimney-assisted greenhouse solar dryer.

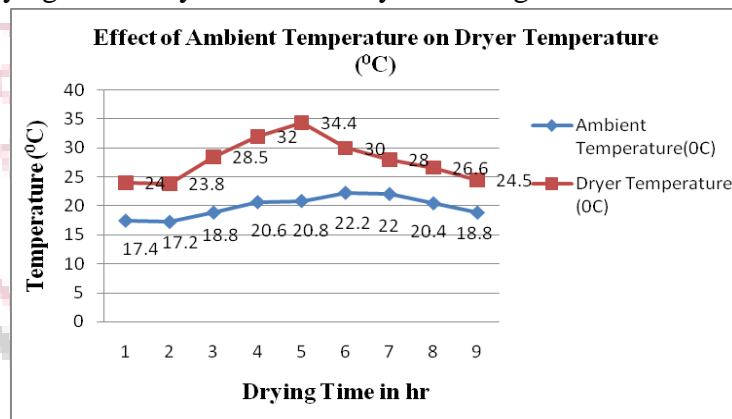


Fig. 1 Effect of Ambient Temperature (°C) on Dryer Temperature during paddy drying experiment in winter season

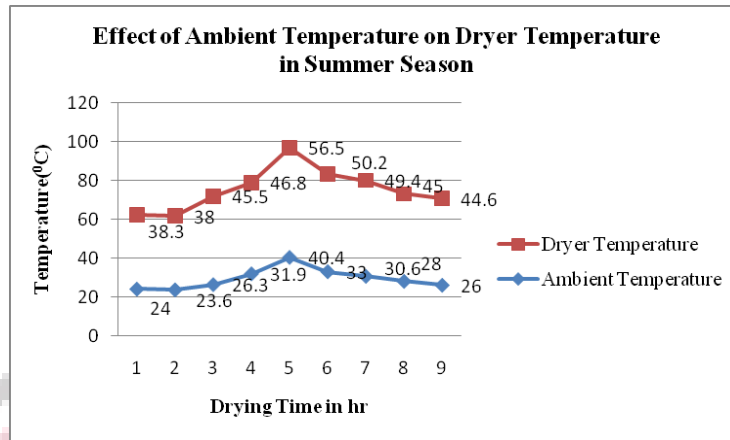


Fig. 2 Effect of Ambient Temperature ($^{\circ}\text{C}$) on Dryer Temperature during wheat drying experiment in summer season

Summary and Conclusion

This study evaluated the drying performance and thermal efficiency of a chimney-assisted greenhouse solar dryer for wheat and paddy under natural environmental conditions. The dryer demonstrated its capability to achieve higher internal temperatures than ambient conditions, resulting in improved drying rates. The thermal efficiency of the system was found to be 10.25% for wheat and 13.5% for paddy. Moisture content decreased from 18.5% to 15% (wet basis) for paddy and from 17.6% to 14.2% (wet basis) for wheat during an 8-hour drying period. For paddy drying, the maximum and minimum dryer temperatures recorded were 34.4°C and 23.8°C , respectively, while for wheat drying, it was recorded 56.6°C and 23.6°C . The temperature difference between ambient air and the dryer chamber reached up to 16°C for wheat and 12.2°C for paddy. The construction cost of each dryer was approximately 3500 INR (around 40 USD), making it an affordable and suitable solution for marginal and small-scale farmers in India.

Conflict of Interest Statement

The author declares that the dryer design presented in this study has potential commercial applications, and a patent application is planned in the near future. This disclosure is made in accordance with standard publication ethics.

Future Recommendations

Further improvements in thermal efficiency can be achieved through modifications in the design and geometry of the dryer. Optimization of structural and airflow parameters should be considered in future studies to enhance overall performance.

Design Data Availability Statement

All dimensional and design data for the three chimney-assisted greenhouse solar dryers are available with Rajesh Kumar Mishra (first author). This work forms part of the author's PhD thesis in Mechanical Engineering. After submission, the thesis will be published on the

Government of India's Shodhganga (UGC) repository. The design data will be made available upon reasonable request after the thesis is uploaded.

Funding Statement

This research was conducted without external funding. All expenses related to the procurement of materials for the design and fabrication of the chimney-assisted greenhouse solar dryer were borne by Rajesh Kumar Mishra. Fabrication was carried out in the workshop of the Department of Mechanical Engineering, AKS University, Satna (Madhya Pradesh), India.

Acknowledgment

The authors express their sincere gratitude for the support received during the design and testing of the chimney-assisted greenhouse solar dryer. The concept and design of the system were developed by Rajesh Kumar Mishra, who led the overall development process. The valuable assistance of Dr. Shrihar Pandey in setting up the experimental system, conducting trials, and recording data is gratefully acknowledged. Their contributions played a significant role in the successful completion of this study.

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