

A Review on the Characterization of High-Moisture Food Products Using Greenhouse Solar Dryers

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Abstract: Greenhouse solar dryers represent a sustainable and efficient technology for food preservation by minimizing contamination and reducing post-harvest losses. Compared to traditional open sun drying, they offer enhanced drying rates, improved product quality, and better protection against environmental factors. The integration of advanced features such as forced convection, phase change materials, and hybrid energy systems further improves drying performance and energy efficiency. Despite these advantages, challenges such as high initial costs, inadequate infrastructure, and limited research in automation and thermal energy storage persist. Different design configurations have been developed to meet diverse agricultural requirements, ultimately contributing to extended shelf life and improved food security

Keywords: Greenhouse, Solar, Dryer, Moisture, Heat Transfer

I. INTRODUCTION

Foods with high moisture content, like fruits, vegetables, and fish, are prone to spoilage from microbial growth [6-10]. Traditional sun drying, while common, is inefficient and can lead to contamination and nutrient loss [11-12]. Greenhouse solar dryers offer a controlled environment that overcomes these limitations, enhancing drying efficiency and preserving nutrients [13-15].

Researchers continuously optimize solar dryers, focusing on efficiency, cost-effectiveness, and adaptability to various climates and foods [16-20]. Studies show that pre-treating foods chemically can significantly reduce drying times [21-25]. Innovations such as indirect solar dryers with forced air and heat storage have successfully produced high-quality products meeting international standards [26-30]. Simple, affordable drying methods are crucial for small enterprises and rural communities, improving product quality and food safety [31-32].

Technological advancements include long-lasting drying systems, improved efficiency, integrated storage, and compact collector designs [33-35]. Systems using water-to-air heat exchangers maintain continuous drying, even without sunlight [36-40]. Solar crop dryers can reduce dependence on fossil fuels and enhance the quality of dried crops like grains, grapes, and onions, minimizing post-harvest losses [41-42]. Solar photovoltaic cells can power active solar dryers, making them ideal for remote rural farms [43-45].

The integration of phase change materials (PCMs) enhances thermal performance, although improvements in thermal conductivity are needed [46-50]. Hybrid dryers, combining direct and indirect solar drying, are inexpensive and suitable for cereals, tomatoes, and mangoes [51-55]. Software simulations and AI techniques are valuable in designing and optimizing solar drying systems, saving time and resources [56-60]. Furthermore, solar drying technologies can significantly reduce CO₂ emissions, contributing to sustainable policies [61-65].

Overall, advancements in greenhouse solar dryers, energy storage, and controls are improving drying efficiency and food security [66-70]. Continued research in materials, heat transfer, and hybrid technologies will further enhance efficiency and economic feasibility, making solar drying a transformative solution for food preservation, especially in energy-deficient regions [71-80]. Table 1 shows the recent contributions of solar greenhouse dryer's research. The objective of



the present research paper is to review the characterization and heat transfer analysis of high moisture content food using greenhouse solar dryer.

TABLE I. MAJOR CONTRIBUTIONS OF SOLAR GREEN HOUSE DRYERS RESEARCH

S.No.	Solar greenhouse dryers and their significant contribution		
	Major inferences	author and reference	Ref. no.
1	Post-harvest losses in poor countries cause significant food scarcity; solar drying with heat storage minimizes these losses.	J P Ekka and Dhananjay Kumar (2023)	55
2	Tomato flakes were dried using the dryer, which was constructed from paraffin wax and black-painted stones.	Asim ahmed et al. (2023)	56
3	Increasing airflow from 100 to 400 m ³ /h raises the moisture ratio in potatoes, carrots, and apples.	Rasaiah Naveen kumar et al. (2023)	57
4	Solar Air Heaters achieve 38-56% efficiency, with ISGHD systems showing 24-45% thermal efficiency.	A.K.Choudhary and M.K Hazarika (2024)	58
5	The "Drying Triangle" helps select drying techniques; pretreatments and hybrid methods enhance efficiency and product quality.	Satyajit Bhattacharjee et al. (2024)	59
6	Solar hybrid dryers (SHDs) enhance traditional drying, rival fossil fuels, offer control, and improve environmental impact.	Chayan Kumer Saha et al. (2024)	60
7	60°C is the optimal dehydration temperature for Kent mango slices, balancing energy use and efficiency.	Campo et al. (2025)	61
8	FGD reached 52°C in potato slices; NGD and OSD showed lower temperatures, suiting high-moisture crops.	Egbal Elmsaad et al. (2024)	62
9	Researchers enhance solar dryer efficiency using hybrid systems, desiccants, heat storage, and auxiliary heating for better drying.	Kavati Venkateswarlu and S. V. Kota Reddy (2024)	63
10	Helical (HSAH) and spiral (SSAH) solar air heaters both achieve approximately 65% thermal efficiency at high mass flow rate	Amara et al. (2025)	64

II. CHARACTERIZATION OF HIGH-MOISTURE CONTENT FOODS

A. High-Moisture Content Foods

Moisture content is a key characteristic of high-moisture foods, influencing drying time and energy needs [2,3,7,9]. Drying prevents degradation and enables storage [19,20]. The drying rate depends on moisture diffusion factors, including initial and final levels, and safe moisture levels which reduce microbial and enzymatic activity [26,31]. Adjusting mass flow rates allows manipulation of the greenhouse's internal temperature [39,44]. The ideal drying temperature for agricultural products ranges from 45 to 70 degrees Celsius [45,60]. Table 2 shows limits for drying various crops, considering their starting and ending moisture levels.

III. GREENHOUSE SOLAR DRYERS: OVERVIEW

Greenhouse solar dryers use solar energy to create controlled drying environments for food preservation. Key components include a transparent cover, a drying chamber for air circulation, and often a thermal storage system for consistent efficiency. Solar dryers are classified based on design and operation.

A. Natural convection solar dryers:

Researchers have extensively developed and investigated a wide range of solar dryer technologies aimed at improving rural food preservation practices and reducing post-harvest losses [66–69]. These innovations include cost-effective



natural convection dryers that operate without external power, modified designs incorporating reversed absorber plates to enhance heat absorption efficiency, and hybrid systems integrated with biomass backup to ensure continuous drying under low solar radiation conditions. In addition, several dryers have been specifically optimized for different agricultural products such as grapes, cassava, bananas, and mangoes, taking into account their unique drying characteristics and moisture content. Figure 1 presents a typical configuration of a natural convection solar dryer combined with a biomass backup system, demonstrating its suitability for rural and off-grid applications [67].

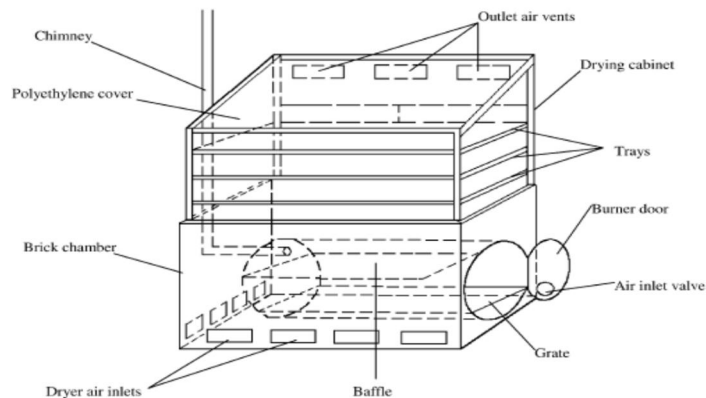


Fig. 1. Natural convection solar dryer with biomass back-up [67]

B. Greenhouse solar dryers

Greenhouse solar systems optimize agricultural drying using microcomputer controls. Researchers used numerical modelling and thermal storage to dry tobacco, longans, bananas, and onions [70-71]. Simulations and experiments enhance efficiency, demonstrating sustainable, year-round agricultural potential. Pictorial view of the greenhouse solar dryer [70] as depicted in Fig. 2.



Fig. 2. Pictorial view of the greenhouse solar dryer[70]

TABLE II. TEMPERATURE LIMITS FOR DRYING VARIOUS CROPS, CONSIDERING THEIR STARTING AND ENDING MOISTURE LEVELS.[7,26]

Crop	Temperature limits for drying various crops, considering their starting and ending moisture levels		
	Initial moisture Content (wb%)	Final moisture Content (wb%)	Maximum allowable Temp. (°C)
Pulses	20–22	9–10	40–60
Oil seed	20–25	7–9	40–60
Green Peas	80	5	65
Cauliflower	80	6	65



Paddy, raw	22-24	11	50
Paddy,	30-35	13	50
Maize	35	15	60
Wheat	20	16	45
Corn	24	14	50
Rice	24	11	50
Onion	80	4	55
Garlic	80	4	55
Cabbage	80	4	55
Guavas	80	7	65
Okra	80	20	65
Pineapple	80	10	65
Tomatoes	96	10	60
Brinjal	95	6	60
Sweet	75	7	75
Potatoes	75	7	75
Chilies	80	5	65
Apricot	85	18	65
Apples	80	24	70
Grapes	80	15-20	70
Bananas	80	15	70
Maize	35	15	60
Wheat	20	16	45
Corn	24	14	50
Rice	24	11	50
Carrot	70	5	75
Green	705	5	75

C. Indirect type solar dryer:

Madhlopa and Ngwalo developed an indirect natural convection solar dryer with integrated collector-storage and biomass heaters[72]. Drying pineapples, they measured moisture pickup efficiencies of 15% (solar), 11% (biomass), and 13% (combined). Optimized airflow improves efficiency by reducing collector air gap[72]s. Figure shows the Cross-sectional representation of the indirect solar dryer, highlighting the relative positions of the burner, collector, drying chamber, and solar chimney.

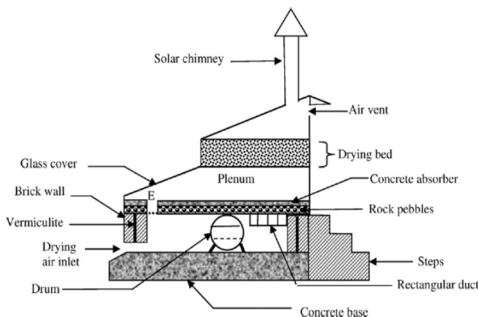


Fig. 3. Cross-sectional representation of the indirect solar dryer, highlighting the relative positions of the burner, collector, drying chamber, and solar chimney[72]



D. Indirect type solar dryer:

Studies on cabinet solar dryers reveal that air temperature impacts drying rate, while airspeed has a minimal effect. Models predict temperature and drying dynamics [73-76]. A dual-compartment dryer for fruits and vegetables proves more cost-effective than electric drying, with reverse flat-plate absorbers improving efficiency. Figure 4 shows the Illustration of a cabinet-type solar dryer setup [76].



Fig. 4. Illustration of a cabinet-type solar dryer setup [76]

E. Hybrid greenhouse dryers

Hybrid Greenhouse Dryers (HGDs) combine solar energy with biomass/electricity for efficient drying [21,50,60]. A portable solar tunnel dryer, using a PV system and flat plate collector, reduced peppermint drying time compared to sun drying [21,50,60]. Kushwah et al. developed a Heat Exchanger Evacuated Tube Assisted Drying System (HE-ETADS) for drying mushrooms [21,50,60]. HGDs effectively reduce postharvest losses in fruits, vegetables, and fish [21, 50,60] . Compared to electric dryers, hybrid setups reduce drying time and improve temperature distribution, enhancing product quality [21, 50,60] .

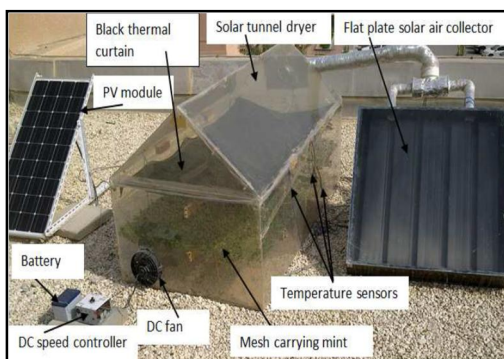


Fig. 5. Hybrid solar tunnel dryer experimental setup with PV and flat plate enhancements [21]

IV. CONCLUSION

Greenhouse solar dryers offer a sustainable, efficient method to preserve food by reducing contamination and post-harvest losses. Compared to open sun drying, they provide faster drying, better protection, and improved product quality. Technologies like forced convection, phase change materials, and hybrid energy sources boost performance, ensuring operation even in poor weather. Despite benefits, challenges include high initial costs, limited infrastructure, and the need for more research in automation and heat storage. Drying efficiency depends on thermal properties, moisture content, and heat transfer. Designs vary natural convection, cabinet, tunnel, and more—each suited for specific agricultural drying needs and shelf-life extension.



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