Comparative Analysis of Direct Type Solar Tunnel/Greenhouse Dryer and Indirect Type Solar Dryer for Sustainable Drying Solutions

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Abstract: Efficient food preservation is essential to tackle global food security challenges, particularly in developing countries where post-harvest losses reach 30–40%. Open sun drying (OSD) remains inefficient and prone to spoilage, underscoring the need for advanced methods. This study evaluates direct solar tunnel/greenhouse and indirect solar dryers as sustainable alternatives. Indirect solar dryers provide better control over drying conditions, offering protection against environmental factors for diverse materials. Solar tunnel dryers, with scalable designs and space efficiency, are suited for large-scale agricultural drying. The current study emphasizes advancements in solar dryer designs, including energy storage integration, optimized orientation, and airflow management, to enhance drying efficiency, reduce energy consumption, and maintain product quality. By leveraging renewable energy, these technologies address post-harvest losses, ensuring food security and promoting environmental sustainability. Solar drying emerges as a viable, eco-friendly solution for agricultural preservation, aligning with global efforts to mitigate food wastage and economic instability.

Keywords: Solar dryer, solar drying, Solar tunnel dryer, Indirect solar dryer

1. INTRODUCTION

Controlling and reducing food wastage from harvesting to market distribution is essential to address the worldwide challenge of balancing a growing population with food availability. Lack of effective processing methods and inadequate cold storage facilities can cause food spoilage, affecting its quality, taste, color and aroma. After harvesting, the losses were estimated as 30 to 40% of total production of fruit and vegetables, which is a significant loss for many developing countries in the agricultural sector [1]. This contributes significantly to the escalation of food prices. Since drying extends shelf life, enhances product quality, and minimizes loss during storage, it is extensively acknowledged as an essential method for preserving agricultural produces [2], [3]. There are numerous drying technologies available in the commercial market for agricultural products, and each has pros and cons of its own. In many developing countries, OSD is generally used for the preservation of grains and food. Although this method is the cheapest method, it is prone to spoilage due to direct exposure to the environment such as rain, dust, animals, wind and insects and direct sunlight [4]. Thus, attempts have been made to go from OSD to controlled solar drying in order to produce dried products of a higher quality.

Drying processes are progressively avoiding conventional energy sources like fossil fuels and grid electricity because of their negative effects on the environment, their financial consequences, and their concerns about the sustainability of resources [5]. The combustion of fossil fuels in traditional drying methods releases pollutants and contributes to air pollution and climate change, aligning poorly with the global push for sustainable practices. Additionally, the costs associated with fossil fuels can be unpredictable and subject to market fluctuations, making them less attractive for long-term planning [6]. As a result, businesses and industries are increasingly turning to solar energy as a cleaner, more sustainable option for drying processes [7].

Drying products using sun's energy is a cost efficient and sustainable approach that aligns with environmental conservation. Beyond its environmental benefits, solar drying also offers effective cost savings, as it relies on freely available sunlight once the initial setup costs are covered [8]. Technological advancements have improved the efficiency and reliability of solar drying, making it an increasingly attractive option for businesses and communities seeking sustainable and community-oriented solutions [9].

Open sun drying, a traditional moisture removal method, faces limitations due to its weather dependency, contamination risk, slow drying rate, and inconsistent drying [10]. Vulnerable to weather changes, it struggles with interruptions and contamination risks, impacting product quality. Seasonal applicability, vulnerability to pests, material limitations, and quality concerns highlight the need for alternative drying methods in industries requiring specific standards [11].

Using solar radiation, the process of "solar drying" eliminates moisture from a variety of things, including food, textiles, agricultural products, and other items. By using the sun's heat, this technique lowers the materials' moisture content and extends their shelf life by promoting evaporation [12]. Fig. 1 depicted solar drying systems, typically consist of a collector to capture sunlight, an absorber to absorb heat of solar radiation and a chamber for drying [13].

Solar dryers are characterized into natural (passive) convection type dryers and forced (active) convection type dryers, providing solution for the limitations of open syn drying. Natural convection method uses buoyant force to generate airflow whereas forced convection method uses electric driven blower or fan. These dryers are further divided into four categories in both natural and forced convection as shown in fig 2.

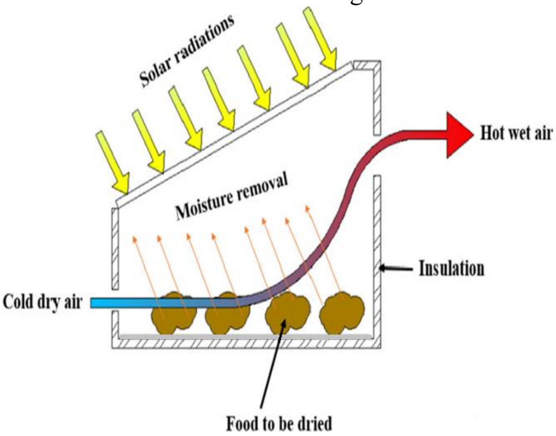

Figure 1: Working principle of solar dryer [14]

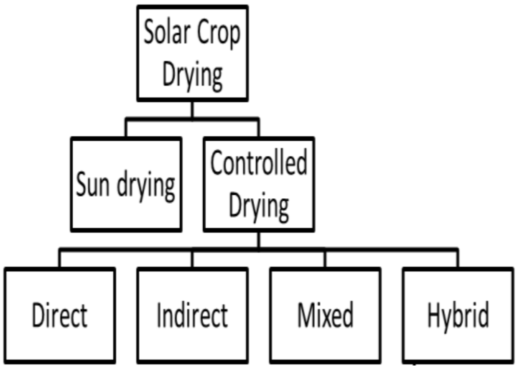

Figure 2: Categories of Solar Dryers

Direct solar dryers feature a transparent-covered box or greenhouse where products are placed on trays, directly subjected to sun energy [15]. In indirect type dryers, SACs are used for air heating, with a drying cabinet and chimney for moisture transfer. Mixed-mode dryers combine elements of both direct and indirect types, utilizing heat of direct solar radiation and heated air from SAC. Various auxiliary heat sources like waste heat, biomass, or electricity are used in hybrid solar dryers enhance evaporation of food moisture [16].

Table 1: Drying attributes of various agricultural produces [17]

Product	Moisture Content		Max. Allowable Temperature (°C)	Drying Time (h)
	Initial (%)	Final (%)		
Onions	85	6	55	48
Onion flakes	80	10	55	24
Onion rings	80	10	55	
Tomatoes	95	7	60	36
Green peas	80	5	60	8–10
Grapes	80	15–20		32–40
Applies	82	11–14	65–70	24–26
Coffee beans	55	12	–	
Bananas	80	15	70	15
Cassava	62	17		
Cocoa beans	50	7	–	
Tobacco	90	10		96
Coffee	65	11		288
Garlic flakes	80	4		48
Chilies	80	5		48
Ginger	80	10		168
Cabbage	80	4	65	48
Tea	80	3		96
Pepper	71	13		48
Turmeric	80	10		120
Potato chips	75	13	70	72
Paddy, raw	22–24	11	50	
Paddy, parboiled	30–35	13	50	
Maize	35	15	60	

Figure 3 illustrates the statistics of research articles published on solar drying. In Figure 3(a), the country's leading in research on solar drying are reported, with India ranking as the second-highest contributor. Over the last two decades, a total of 8362 articles have been published, depicting an upward trend, as shown in Figure 3(b). The selection of a suitable dryer type, whether direct (Tunnel/greenhouse) or indirect, poses a challenge for consumers. Figure 3(c) showcases the annual trends in articles published on indirect type dryers, while Figure 3(d) focuses on tunnel/greenhouse type dryers. Table 1 provides consumers with information on drying various agricultural produce.

The objective of this review is to evaluate and compare the performance, efficiency, and sustainability of direct solar tunnel/greenhouse dryers and indirect solar dryers, highlighting their advantages, limitations, and potential applications for promoting sustainable drying solutions.

2. INDIRECT SOLAR DRYERS

Figure 4 depicted Indirect solar dryer, in which collectors are used which collects solar heat and transfer it to drying chamber increases control over drying conditions. [18]. Parikh and Agrawal [19] performed experiments and investigated a double-shelf solar dryer assisted with a FPC. The study focused on Capsicum annum which is green chilli and S. tuberosum that is potato chips. Glazing covers, specifically poly-carbonate sheets and glass glazing were used to increase the solar dryer's efficiency. By using glass glazing significant increase in efficiency, having range from 9.0–12.0% to 23.7%, while the polycarbonate sheet yielded an efficiency of 18.5%. Maiti et al. [20] developed a design and conducted test an ITSD which utilizes natural convection, provided with reflectors. The study demonstrated that the collector's efficiency was significantly enhanced from 40% to 58.5% under the condition of no load by using reflectors at maximum solar radiation condition.

Sanghi et al. [22] used Ansys software to model corn drying in an ITSD, validating results with experimental data. Essalhi et al. [23] experimented for drying of grapes in an ITSD and the results were compared with OSD. Grapes were dehydrated from 79.8% to 20.2% moisture content (wb) in 120 hours. Tedesco et al. [24] analyzed the drying of apple in passive indirect dryer having a chimney. Erick et al. [25] dried tomato slices of 7.45 kg in a FPC connected ITSD, achieving a moisture content reduction from 93.81% to 6.54% in 26 hours, with estimated efficiencies of 55.45% (collector) and 8.80% (drying).

Kadam and Samuel [26] employed an active V-grooved Solar Air Collector (SAC) assisted solar dryer for drying Brassica oleracea (cauliflower). The results reported maximum temperature enhances of 13.5°C at collector outlet, with an 61.5% average thermal efficiency. Hossain et al. [27] innovatively developed a Hybrid ITSD featuring a solar reflector for drying 20 kg of halved tomatoes. The collector outlet exhibited a temperature increase of 30 °C above ambient conditions. Drying 20 kg of tomatoes in 2 kg batches achieved a drying efficiency ranging from 17% to 29%. The researchers recommended pre-treatment with sodium metabisulphite before drying, especially if the drying temperature falls below 45 °C, to prevent microbial growth.

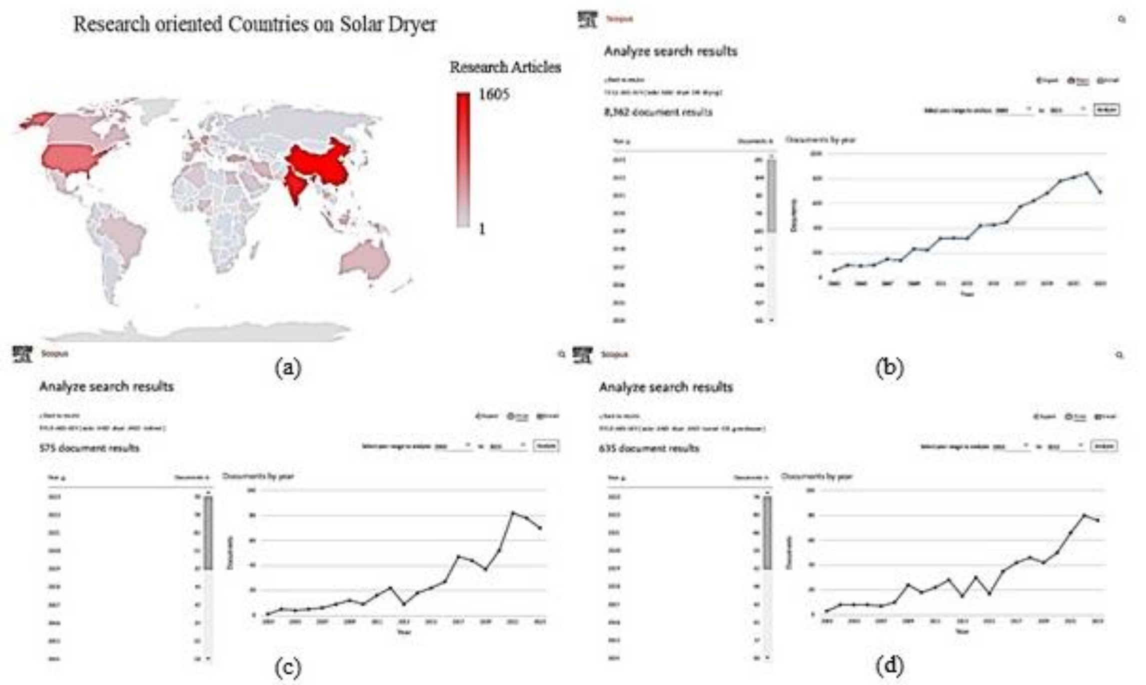

Figure 3: Statics of published papers on solar dryers, (a) Research oriented countries on solar dryer, (b) Trends of articles published on Solar drying/dryer; (c) Trends of articles published on indirect solar dryers, and (d) Tunnel/greenhouse dryer

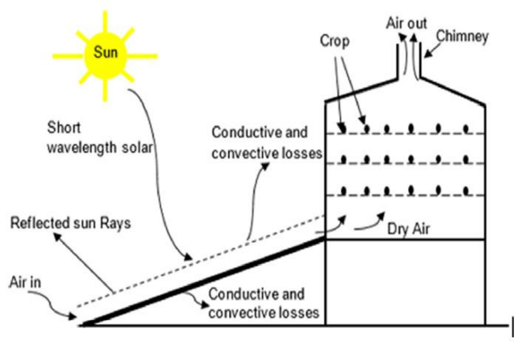

Figure 4: Indirect Type dryer with Solar collector [21]

Singh [28] introduced an active ITSD specifically tailored for the drying of thin layer silk cocoon (Bombyx Mori). The cocoon was significantly dehydrated from 60% (wb) to 12% (wb) with the temperatures between 50-75 °C. Sundari et al. [29] investigated evacuated tube collector assisted active ITSD. The bitter gourd was dehydrated to 6.25% from 91% (wb) within a 6-hour timeframe. Additionally, DR and MR were estimated and compared with OSD, revealing a superior quality product obtained through the ITSD method as opposed to OSD. Mathew and Thangavel [30] developed an evacuated tube collector assisted dryer with thermal energy storage. The SAC energy efficiency was ranged from 1.9% to 5.6%. During the study, the air provided by SAC reached a maximum output temperature of 118°C. The dryer has a 2.6-year payback time. Ringeisen et al. [31] dried tomatoes in solar dryer assisted with solar concentrators. The tomatoes were dehydrated from 90% to 10% (wb). When tomatoes were dried using a solar concentrator, the drying time was found to be 21% less than when tomatoes were dried using dryers without a concentrator.

Figure 5 represents the evacuated tube assisted ITSD. To dry the pumpkin slices, Malakar and Arora [32] conducted experiments using PCM aided evacuated tube dryer at varied air mass flow rates. The results reveled the 36.33 °C hike in the average temperature of dryer chamber. The dryer maintains the temperature in evening hours and prolonged the drying process by two hours. A solar dryer assisted with evacuated tubes collector that can hold several kinds of thermal energy storage media was created and analyzed by Mathew et al. [33]. The collector and dryer's energy efficiency reached their maximum value of 29% and 24%, respectively, and the thermonol-55 heat storage medium reached its maximum temperature of 118°C.

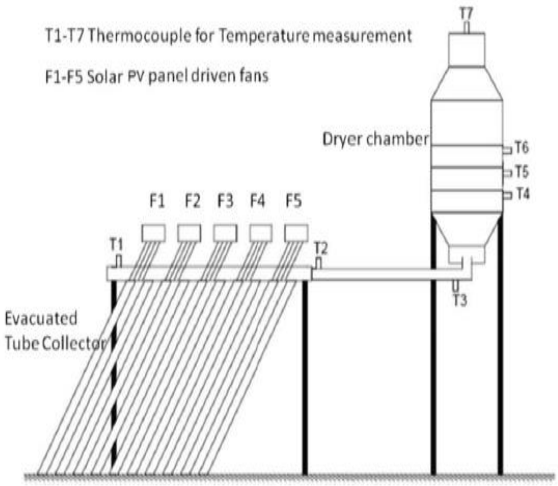

Figure 5: Representation of ETSD [35]

Table 2: Advantage and disadvantages of indirect solar dryers

Advantages	Disadvantages
• Prevents direct sunlight from hitting the produce, reducing the risk of discoloration and degradation of sensitive nutrients. • Operate in various weather conditions, can dry products even in partially cloudy conditions. • Precise control over temperature and humidity. • A closed system protects materials from dust and elements. • Suitable for a wide range of materials • Adaptable to both small and large-scale drying operations.	• Higher initial investment costs due to added components. • It has a more complex design with added components for heating. • May require additional energy sources for continuous drying. • Due to the lower flow rates, the performance of passive dryers was very poor. Hence, air circulating fan is required.

Daghigh et al. [34]. The dryer maintains the maximum air temperature of 45.5 °C. Wang et al. [36] introduced an active ITSD for mango drying equipped with heating source. At 52°C, the drying rate was 1.67 kg water/kWh, and average thermal efficiency varied between 30.9%-33.8%. Additionally, a comparable forced convection investigation on the drying of red chilies was carried out by Téllez et al. [37]. Potdukhe and Thombre [38] created an absorber-equipped thermal storage mechanism assisted ITSD. Using thermic oil as the energy storage medium, their investigations concentrated on fenugreek leaves and chilies. The results reported the collector and drying efficiency of 34%. of 21% respectively and a Despite a system cost increase of approximately 10% due to thermic oil, the noteworthy 40% reduction in drying time underscored the economic viability of this approach. Singh and Vardhan, [39] experimented evacuated tube air collector having helical coil inserted assisted solar dryer at different flow rates of air. The average temperature and maximum temperature of air were recorded 95.5°C and 112.6°C respectively with the helical inserts at an air mass flow rate of 0.003 kg/s.

Jain and Jain [40] presented a model with the goal of assessing the effectiveness of a flat plate SAC combined with TES for crop drying over several trays. When there was no direct sunlight, the TES was essential in heating the drying air. Kareem et al. [41] dried Roselle in SAC assisted drying system. Sensible heat (SH) was stored in the system using granite. Calculations were made for several efficiencies, including the system optical efficiency (70.53%), drying efficiency of 36.22%, moisture pickup efficiency (67%), and collector efficiency (64.08%). The results reported the saving of 21 hours as compared to OSD with the payback period of 2.14 years.

Akhijahani et al., [42] performed drying in parabolic trough collector assisted indirect solar dryer for drying Rhubarb slices. According to the findings, there was a 2.32–8.21% increase in total drying efficiency and a 1.91% decrease in specific energy usage when partial recirculation of air was used. The range of the energy efficiency is 35.4 to 61.3%. The Table 2 represents advantages and disadvantages of indirect type solar dryers.

3. SOLAR TUNNEL/GREENHOUSE DRYERS

The unique design, featuring a tunnel-shaped structure with a transparent cover, allows for the efficient utilization of ample space as shown in Figure 6. This characteristic becomes particularly valuable when drying substantial quantities of agricultural produce. The extended length of the tunnel accommodates a larger drying area, making it well-suited for bulk drying operations [43].

Figure 6: Illustrative view of Solar Tunnel Dryer [44]

Janjai et al. [45] experimented peeled longan and banana drying in photovoltaic assisted dryer through experiments and simulations. The drying temperatures for longan ranged between 30°C-60°C, whereas banana ranged between 31°C-58°C. Drying times within the greenhouse were notably shorter, with longan drying in 3 days and banana in 4 days. Comparative analysis revealed superior color and taste in products dried within the greenhouse. Rabha et al. [46] investigated the solar air heater (SAH) assisted indirect type dryer to dry ghost chilli. The ghost chilli sample was dried in 123 hours from 589.6% (db) to 12% (db) moisture content, whereas open sun drying required 193 hours. Tiwari and Tiwari [47] proposed partially covered PVT solar collector assisted solar dryer. Equivalent thermal energy and energy efficiency were varied from 3.24-10.57 kWh/day and 28.96%-19.11%, respectively, when the number of solar collectors is changed from one to five. Gupta et al., [48] investigated PVT collector based dryer for drying tea under active and passive mode. The energy performance due to the PVT collector was enhanced to 58.71% on sunny days. The MMD process has the maximum efficiency of 26.37%, SMER of 0.6125 kg/kWh and moisture effective diffusivity of 4.97×10^{-9} m^2/s.

Natarajan et al., [49] studied aluminum filings, rock bed, and sand bed as heat storage materials in the drying chamber floor to maintain the temperature in night hours. The dehydration time of Vitis vinifera and Momordica was reduced by 27 h and 6 h with and without TES respectively as compared with OSD. The TES materials enhanced the average efficiency by 2-3%. The maximum thermal efficiency of 19.6% was obtained with the sand among the thermal storage materials used. Gopinath et al., [50] designed an active dryer having paraffin wax to improve the performance of dryer in no sunshine hours. The results reported that seeded grapes were dried effectively in shorter duration in PCM based solar dryer. Figure 7 reported the various shapes of tunnel/greenhouse solar dryer.

Sethi and Arora [52] enhanced the performance of greenhouse dryer by incorporating aluminized polyester sheet for reflection on the inclined north wall. The floor area was 4×6 m^2 and the dryer was covered with polyethylene sheet. Results represented overall drying time that reduced in both passive and active convection by 13.13% and 16.67%. Barnwal and Tiwari [53] developed a forced mode hybrid greenhouse dryer assisted with PV/T having capacity of 100 kg installed in the IIT Delhi, India. For two grape types, coefficient of convective heat transfer was measured and compared in both open and greenhouse condition using the PV/T drier.

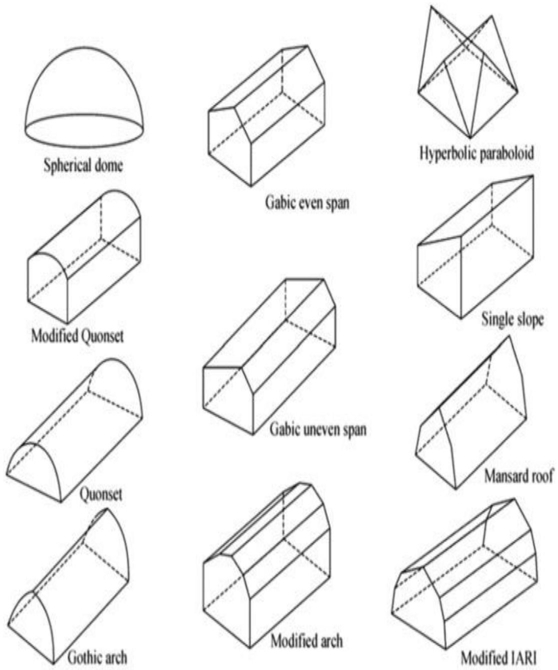

Figure 7: Different shapes of tunnel/greenhouse solar dryers [51]

Almuhanna [54] developed a even span type gable tunnel dryer for date drying at King Faisal University, Saudi Arabia, aiming to assess its performance. The average efficiency of the developed dryer attained 60.11% throughout the experimental period. Adu et al. [55] developed a dryer in tent form in Nigeria.

The floor and its walls are fully covered with cloth having black color Okra's starting moisture content of 86.05% was reduced in 23 hours to 3.43% final moisture content at a temperature of roughly 50 °C. Prakash and Kumar [56] assessed a modified even span type dryer. The investigation was organized under two conditions viz without and with enveloped floor with black PVC sheet.

It was observed that covering the floor led to elevated temperatures inside the chamber and a reduction in relative humidity. Prakash and Kumar [57] was tested greenhouse type dryer having opaque northern wall with different concrete floors: (a) coated with black PVC sheeting and (b) left exposed. A more noticeable rise in temperature and decrease in humidity was seen on concrete floor covered with black PVC sheet.

Dhanore and Jibhakate [58] conceptualized, constructed, and implemented a solar greenhouse dryer at KITS, Nagpur, India, specifically designed for the red chili drying. The dryer was made of a wooden frame enveloped with polyethylene having the dimensions of 1 ft × 2 ft × 6 ft. For the drying, two trays of 2 ft × 2 ft were used and to maintain a consistent airflow rate, a fan and chimney were incorporated into the system.

Table 3: Advantage and disadvantages of solar tunnel dryer

Advantages	Disadvantages
• Simpler in design, which can make them easier and cheaper to construct and maintain. • Large material will accommodate in small design. • Primarily rely on solar energy, reducing the need for electricity or fossil fuels even for circulation for air • Transparent cover shields against external factors. • Efficient for large-scale drying of agricultural produce. • Well-suited for larger spaces, making it scalable.	• Direct exposure to solar radiation lowers product quality. • Potential cost for construction but often more cost-effective over time.

The solar tunnel dryer demonstrated a notably higher drying rate compared to natural sun drying. Tables 3 reported the advantages and disadvantages of solar tunnel/greenhouse type dryers.

Table 4 presents a comparative analysis of direct solar tunnel/greenhouse dryers and indirect solar dryers, highlighting key performance parameters, Quantitatively and Qualitatively.

Table 4: Comparative analysis of direct solar tunnel/greenhouse dryers and indirect solar dryers

Parameter	Direct Solar Tunnel/ Greenhouse Dryer	Indirect Solar Dryer	Remarks/Justification
Drying Efficiency (%)	35–55 approx.	42–68 approx.	Indirect dryers exhibit higher efficiency due to controlled drying conditions.
Drying Time (hours)	8–10 for Potato slices	6–8 for potato slices	Faster drying in indirect systems due to optimized airflow and insulation.
Product Quality	Moderate (prone to contamination)	High (protected from external factors)	Indirect dryers ensure better protection against dust, pests, and environmental contaminants.
Energy Utilization	Utilizes solar energy directly but less efficient	Improved utilization with integrated energy storage systems	Energy storage enhances reliability and drying continuity in indirect dryers.
Scalability	Suitable for large-scale agricultural drying	Better for small- to medium-scale operations	Solar tunnel dryers are more feasible for bulk drying due to their larger drying area.
Environmental Impact	Low but less efficient space utilization	Low, with higher efficiency	Both systems are environmentally friendly, but indirect dryers make better use of energy resources.

4. METHODS FOR ENHANCING DRYER PERFORMANCE

There are several methods that contribute to enhancing the performance of solar dryers. (a) A well-designed solar dryer with proper insulation, reflective surfaces, and effective airflow distribution can maximize heat transfer and minimize energy loss, improving overall efficiency. (b) Proper orientation of the solar dryer towards the sun and locating it in an area with maximum sunlight exposure can increase solar energy absorption and enhance drying efficiency. (c) Using high-quality solar collectors with efficient heat absorption and transfer capabilities can boost the amount of solar energy captured and utilized for drying. (d) Integrating heat storage devices such as TES systems and batteries allows solar dryers to store energy during intense solar radiation. The stored energy can be used at night or in cloudy conditions to keep drying processes going without interruption. (e) Adequate insulation of the drying chamber minimizes heat loss and maintains consistent temperatures inside the dryer, improving energy efficiency and reducing drying time. (f) Efficient airflow management within the drying chamber ensures uniform distribution of heated air, facilitating even drying of the materials and maximizing drying efficiency. (g) Regular maintenance and cleaning of solar dryer components, including collectors, vents, and insulation, ensure optimal performance and prolong the lifespan of the equipment, contributing to long-term efficiency. (h) In hybrid dryers, integration of auxiliary heat sources, e.g. waste heat, biomass or electricity can supplement solar energy during periods of low sunlight or enhance drying efficiency during adverse weather conditions. By considering and optimizing these factors, the efficiency of dryers can be significantly improved, leading to reduced energy consumption, shorter drying times, and higher-quality dried products.

5. CONCLUSIONS

Addressing post-harvest food wastage, estimated at 30-40%, is critical for food security in developing countries, reducing economic instability. Traditional methods like open sun drying face challenges, while solar drying provides a sustainable, cost-effective solution for preserving agricultural produce.

Various solar dryers e.g. direct, mixed mode, indirect and hybrid mode, addressed the weaknesses of open sun drying. With the ability to precisely control over temperature and humidity, indirect sun dryers protect products from environmental factors and are adaptable to various materials. Advancements in this category, such as ITSDs, SACs, and hybrid configurations, showcase increased efficiency and effectiveness. Solar tunnel dryers, with their scalability and efficient use of space, present advantages over direct solar dryers in large-scale agricultural applications.

In essence, the evolution of drying technologies and the increasing adoption of sustainable practices are crucial steps towards mitigating food wastage and promoting a more environmentally friendly approach to agricultural preservation. As technology continues to advance, solar drying is poised to play a pivotal role in achieving a balance between demand and supply of food in a fast-developing countries.

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