SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Design and Performance of Solar Tunnel Dryers: A Comprehensive Review

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ARTICLE INFO

Article history:
Received 5 June 2026
Received in revised form 5 August 2026
Accepted 10 August 2026
Available online 17 August 2026

Keywords:

Solar tunnel dryer; drying performance; thermal efficiency

ABSTRACT

An inadequate postharvest preservation results in considerable food loss, especially in poor areas where there is little access to efficient drying processes. Open sun drying is the traditional approach but is typically associated with contamination, poor product quality, prolonged drying durations and high postharvest losses. The purpose of this review is to assess the design features, drying performance, economic viability and environ-mental impacts of solar tunnel dryers for agricultural products. A detailed review of available literature on direct, indirect and hybrid solar tunnel dryers working under natural and forced convection modes has been performed. The examined studies were analyzed with respect to dryer configuration, drying efficiency, moisture reduction, product quality, economic performance and environmental impact. The results show that solar tunnel dryers may shorten the drying time by around 25–57% compared to the typical open sun drying with superior nutritional, sensory and sanitary quality of dried items. Reported thermal efficiency ranged from about 19% to over 80% as a function of dryer type, operating circumstances and product qualities. Economic assessments indicated positive benefit-cost ratios and short payback times ranging from 1 to 4 years. The thermal energy storage and hybrid energy systems can also improve the performance and continuity of operation of the dryer. In conclusion, solar tunnel dryers are a low-cost, energy-efficient and ecologically sustainable drying technology that can considerably minimize postharvest losses and increase food security, particularly for smallholder farmers and rural populations.

1. Introduction

The world's ever-increasing population has produced food problems for the entire population. This rapid population growth is directly affecting the food balance of any country. Storage facilities are lacking and processing processes are poor, leading to large amounts of food being wasted and inefficiencies in the food supply chain. The quality and quantity of food grains are decreasing day by day. Therefore it was important to avoid food losses during the period of production in order to main-tain a proper balance between the food supply and the increase of the population. But it is not easy to tap the food production potential of small farmers in the countryside. Sunlight drying of food items

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https://doi.org/10.37934/araset.62.5.129144

for preservation in sunny regions emphasized by Sahu *et al*., [1] is one of the key processing techniques. Drying is a simple method of removal of excess amount of water from an agricultural or commercial product. It is the first way of keeping food. The moisture of most of the agricultural products is between 25 and 80% which is greater than the normal of 70% for agricultural products. There is considerably more moisture than is required for long-term preservation. Such moisture content is conducive to rapid growth of germs and fungus on the crops. Bacteria and enzymes may degrade food and remove its nutritive value. Moisture Content of Crops to a Given Level Retards the Operation of Bacteria, Enzymes and Yeasts. "To extend the life of your food, you need to take the water out of it. Another form of drying is the total removal of moisture from foods. When these de-hydrated meals are needed they can be rehydrated back to their original condition was discussed by Chaudhari and Salve [2]. Open-sun drying is the most common method of harnessing solar energy for drying in which the product is spread over a large surface area and exposed directly to sunshine radiation. It is an eco-friendly process although there are some disadvantages Uncovered products can become contaminated with dust, bacteria, rodents, and insects which is unclean and dangerous. Weather fluctuation may also result in longer drying times and lower product quality. Open sun drying is further limited by the uncertainties of sudden downpours, the laborious nature of the procedure, and difficulty working during non-sunshine hours. The advent of solar dryers, in which the objects are kept in enclosed chambers without exposure to the outside environment but yet get the heat energy of in-coming sun irradiation, has effectively tackled the challenges. Solar dryers are low-cost, eco-friendly solar thermal devices that use several methods depending on kind and design of the dryer to capture the heat energy from the incident solar radiation was demonstrated by Deepak and Behura [3]. This dependence on solar radiation indicates that the design and installation of solar dryers should be very carefully conducted. In fact a good design should take into account the type and amount of food to be dried, the amount of sunshine and the length of daylight, the temperature of the site and the cost of the design. There are several methods to travel this design terrain from simple passive systems to complex active systems with fans and temperature control devices. The design can be as intricate as you like, but the main object is always the same: maximum moisture removal, solar energy absorption and ventilation, with minimum heat loss and cost. The drying operation involves the evaporation of the moisture in the material and air movement is necessary to re-move the evaporated moisture. Two primary mechanisms are involved in drying: the diffusion of moisture from inside the substance to the surface and the evaporation of moisture from the surface into the surrounding air. Drying is a mass and heat transfer operation which depends upon the air velocity, humidity and temperature. Once the design is complete, it's important to test the performance of the design to discover how effective and efficient it is. Important features including drying rate, reduction of moisture content and quality of the final product need to be measured and analyzed. The real value of a design outside technical norms, notably from the point of view of farmers and food processors, is given by characteristics like reliability, durability and ease of operation was highlighted by Rana *et al*., [4]. Fig.1 Cold air entering the drying chamber. The air is heated, its ability to hold moisture rises and it takes water from the material being dried, moving it out of the chamber illustrated by Agarwal *et al*., [5].

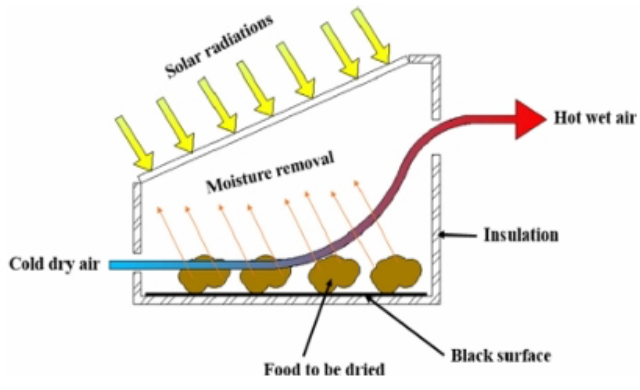

Fig. 1. Principle of solar dryer [5]

Based on the mode of solar energy utilization and airflow arrangement, solar tunnel dryers can be categorized into several types. Understanding these classifications is important because the design configuration directly affects drying performance, product quality, energy efficiency, and operational cost. The main classifications of solar tunnel dryers are summarized as follows.

1.1 Classification of Solar Tunnel Dryers

1.1.1 Direct solar dryer

This form of dryer utilizes direct sun radiation for the dehydration of food items. The hot air supply is generated by solar collectors utilized in the drying unit, where products are dehydrated using solar radiation via a transparent sheet enclosing the chamber. one downside is the worse quality of the product, which may result in a blackened surface owing to direct solar radiation, as well as an extended drying time requirement. Fig.2 illustrates the solar tunnel dryer (Solar Tunnel Dryer), where the products are placed in a thin layer inside the tunnel covered with a UV-stabilized polyethylene sheet. Thermocol is used as insulation to re-duce heat loss, and air is supplied at a specified rate by a DC-operated fan, and fig.3 shows the experimental setup of the dryer, with the products distributed in a thin layer and the hot air passing through the fan inside the tunnel [6,7].

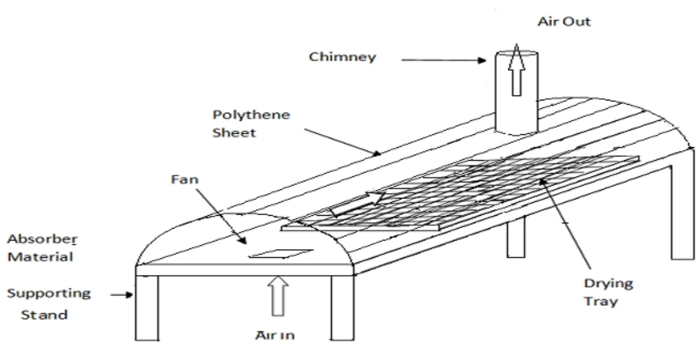

Fig. 2. Schematic of solar tunnel dryer [7]

Fig. 3. Experimental setup [7]

1.1.2 Indirect solar dryer

The solar radiation absorbed by the system is utilized to heat the air passing through the item to be dried. The air is normally heated by convection using the thermal energy of solar radiation absorbed by an independent so-lar collector. In this dryer design, the walls of the drying chamber are insulated to reduce solar radiation and to decrease heat loss through the sidewalls of the dryer. The quality of the product has improved, but it dries more quickly. The dryer fig.4 consists of a solar air-heater collector and a drying chamber containing trays and a fan for air circulation. Eight electric lamps are used to accelerate drying in gloomy weather or after sunset. The dryer is realized efficiently according to the design as shown in fig.5 Figure shows the tilted collector, the drying room, the top fan and the solar plate [6,8].

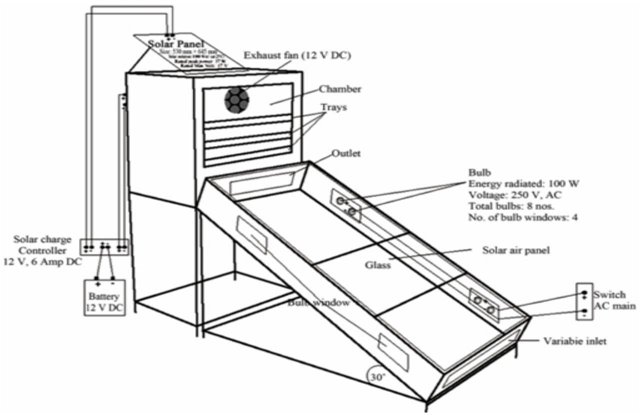

Fig. 4. Design of indirect solar drier [8]

Fig. 5. Indirect solar drier [8]

1.1.3 Mixed solar dryer

The mixed type uses a mixture of heat and indirect drying where hot air from an external solar heater is combined with direct sunlight heating of the product through a transparent roof of the drying cabinet. In contrast, the hybrid system uses a mix of solar heat and an extra heat source (e.g. fossil fuel or biomass) to generate a dual heating effect. Here is an example of the design: The so-lar dryer comprises of two compartments namely the solar collector/heater and the drying chamber. The solar collector fig.6 comprises the glass cover, absorber plate and a heat storage unit with an air input and exit at each end. The drying chamber fig.7 has a hot air intake, fish drying trays and a suction fan at the output to help remove moisture [6,9].

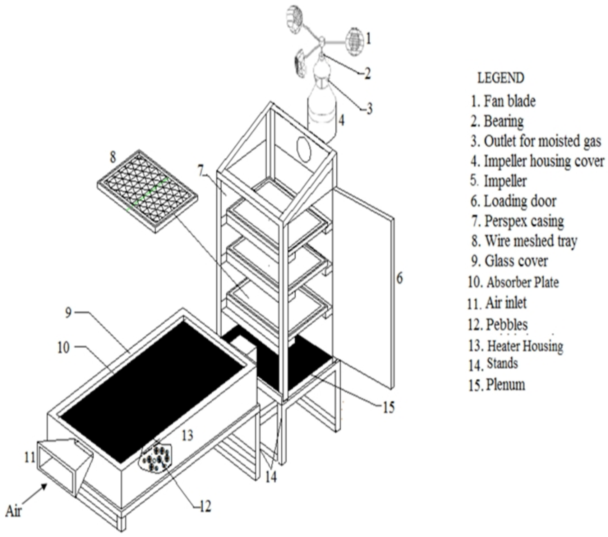

Fig. 6. Skeletal drawing of mixed mode passive dryer [9]

Fig. 7. Fabricated diagram of mixed mode passive solar stock fish dryer [9]

1.1.4 Forced convection and natural convection dryer

The forced convection dryer utilizes a fan or blower to push air through the solar collector and the product and is often called an active drier. In the design of natural convection dryers, the airflow is driven by thermal gradients and these dryers are sometimes called passive dryers. Flow diagrams of natural convection dryers of direct passive and direct active kinds are shown in fig8, demonstrating the air passage via the solar collector and drying chamber [6,10].

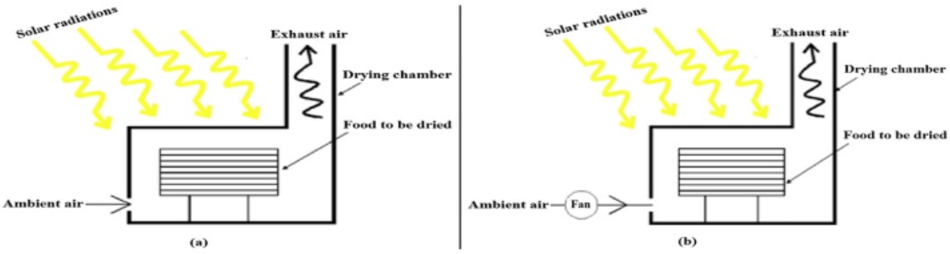

Fig. 8. Natural convection solar dryer a direct passive and b direct active [10]

Much work has been done in earlier research on the various arrangements of solar tunnel driers. They have studied thermal performance, drying efficiency, product quality, economic feasibility and environmental sustainability of their systems for varied working situations. The most important studies are reviewed below, classified by the main types of dryers.

1.2 Previous Work on Solar Dryers
1.2.1 Direct solar dryer

Mohod *et al.*, [11] developed a solar tunnel dryer of 100 kg capacity for fish with a drying chamber area of 10 × 3.75 m constructed with a frame of GI pipe covered with UV-stabilized semi-transparent plastic and having three circular chimneys and axial AC fans to control the temperature and remove humid air. The experimental results showed that the drier reduced drying time by 28% as compared to open solar drying with an average drying efficiency of 19%. Economic analysis revealed a pay-back period of 2.84 years, benefit-cost ratio of 1.21, profitability index of 11.08 and internal rate of return of 23.90, which show the possibility of deploying the solar tunnel dryer as a sustainable alternative to standard fish drying methods.

Mohod *et al.*, [12] designed a walk-in, semi-cylindrical solar tunnel dryer for commercial fish drying with a capacity of 100 kg/batch and drying chamber area of 10 × 3.75 m, GI pipe frame, UV-stabilized semi-transparent plastic covering, three circular chimneys and two axial brushless AC fans to expel humid air and control temperature. The experiments demonstrated that the drier reduced the drying period by 28% compared to open sun drying. The average drying efficiency was 19%. The temperature increase over ambient was 11.24 °C and 18.29 °C for winter and summer no-load tests, respectively. The economic analysis showed a payback period of 2.84 years, a benefit-cost ratio of 1.21, a profitability index of 11.08 and an internal rate of return of 23.90, demonstrating the practicality of the solar tunnel dryer as a sustainable alternative to the traditional techniques of fish drying.

Sookramoon [13] designed and fabricated a solar tunnel drier for rice using a flat plate collector of 2.112 m 2 and a volume of drying chamber of 0.113 m 3. The dry-er was fitted with a DC driven blowers and insulation to minimize heat loss. The performance of the dryer was evaluated and it was found that moisture content of paddy was reduced from 49.96% to 17.64% within 6 hours of drying with an average drying temperature of 67.75°C and thermal efficiency of 22.72%. The battery operated fans maintained the drying air temperature and increased the performance of the dryer. This compact solar tunnel dryer is shown to be an excellent small scale drier for small scale farmers. It dries faster without harming the quality of the crop and shows the promise for sustainable and low cost rice drying.

Basunia *et al.*, [14] designed and constructed a solar tunnel drier to dry fresh dates in Oman. The dryer comprises of a 12 m long and 2 m broad tunnel with a flat plate solar collector, plywood drying section and a 40 W solar powered fan to improve air flow. In two days of sun aided drying, the moisture content of dates was reduced from 32.8% to 18.6% (wet basis) with uniform temperature distribution in the drying chamber and about 36.4% drying efficiency was obtained. The solar tunnel dryer was successful for post-harvest date preservation with faster drying, increased product quality and low-cost and sustainable operation suitable for smallholder farmers.

Massaquoi and Abu [15] built and tested a solar drier of 4 ft x 2 ft to be an environment friendly alternative to the traditional sun drying. The frame was made of bamboo and lumber, the platform of wire mesh, the cover of translucent plastic, and it had a one foot wooden support to keep the food off the ground for best air circulation. A 5-day comparative experiment was conducted using 7 kg of red pep-pers. Results indicated that the solar dryer maintained the inside temperature on average 16.7°C higher than the ambient temperature and shortened the drying peri-od from five days under the sun to three days, while maintaining the quality of the product. The results of the study demonstrated that forced convection sun drying provides advantages such as improved drying efficiency, sanitary operation and eco-nomic benefits to small scale farmers. It is therefore an alternative to sun drying and is sustainable.

Ujunwa *et al.*, [16] designed, produced and evaluated a low cost natural convection solar tunnel dryer for drying of tomatoes, maize and mangoes in Abakaliki, Nigeria. It has a solar chimney, a collection unit, a drying unit and a galvanized iron absorber plate topped with a 200 µm polyethylene sheet and glass for maximum absorption of solar energy and minimum heat loss. Airflow is dependent on natural convection, hence no extra power source is needed. In experimental trials, drying times of 2-3 days were observed at drying temperatures of 25°C to 73°C and 30-50% shorter drying times compared to traditional sun drying, with the quality and nutritional composition of the product remaining unchanged. It was noted that the system is suitable for small-scale, grid-independent operations in developing regions.

Palled *et al*., [17] did a field evaluation of 18 m × 3.75 m solar tunnel drier with shade netting for grape drying at farmer's field in Babaleshwar, Karnataka, India. The semi-cylindrical tunnel was built with 13 GI pipes each of 6 m length, cement concrete floor, UV stabilized 200 µm polyethylene covering and two 1 kW exhaust fans and three roof chimneys to regulate the airflow and humidity. The grapes were dried from 82% (w.b.) moisture content to 14% (w.b.) moisture content in 60 drying hours (8–9 sunny days) versus 140 hours in traditional open shade drying and a net saving of 57.14% in drying time with a dehydration ratio of 4:1, net returns of Rs. 7790/tonne, benefit-cost ratio of 1.26 and payback period of one year.

Ejiko *et al*., [18] devised and manufactured an Azimuth Probe sun drier for maize grains in Nigeria for enhancing post-harvest storage by reducing moisture content from 23% to 12%. The dryer consists of glass covered drying chamber, stainless steel tray, solar reflector, 10 W solar panel, 17 Ah battery and actuator and LDR sensor for automatic sun tracking. The solar radiation passes through thick transparent glass without coming in direct contact with the grain and the actuator adjusts the angle of reflector to absorb maximum energy. Preliminary tests were carried out on 3.85 kg of maize to determine the performance of the dryer. The dryer was efficient in reducing the moisture content of the maize to a safe level for storage with an efficiency of 62% and a coefficient of performance (COP) of 1.16. The dryer was effective, low cost and portable for use by the small scale farmers.

Poonia *et al*., [19] designed, developed and tested a large size PV/thermal hybrid so-lar tunnel drier for drying date palm (Phoenix dactylifera L.) fruits in arid climatic conditions of Jodhpur, India. The dryer consists of a semi-cylindrical metallic frame (6.4 × 3 m) of walk-in type covered with a 6-mm thick UV-stabilized multilayer poly-carbonate sheet, cement concrete black-painted floor and several vertical tiers of perforated drying trays. Fresh air enters through two inlets located strategically near ground level, while a chimney located at the apex of the tunnel expels hot and hu-mid air. The dryer lowered moisture content from 65% to 25% in six days (open sun drying 8 days) with internal temperatures of 44-69 °C (ambient 39.5 °C), thermal efficiency of 36.6%, uniform drying and protection from dust and contaminants during performance evaluation with 250 kg of freshly harvested dates, presenting an effective, scalable and climate-resilient solution for post-harvest processing in arid regions.

Singh *et al*., [20] developed a microcontroller based solar tunnel drier for sustainable drying of turmeric in Meghalaya, India, which is meant to be tolerant to high humidity and wet situations. The dryer is a tunnel of 6 × 5 m with an oval ceiling. It is equipped with 12 corrosion resistant aluminum trays on six platforms, five 10 W DC exhaust fans, an air entrance with a slide adjustable flap, and DHT22 sensors connected to an Arduino Mega 2560 to control the airflow and the operation of the fans according to real-time temperature and humidity. Tests on 100 kg of sliced turmeric indicated that the dryer reduced the moisture content from 71.62% to less than 10% (w.b.) in 101 hours 40 minutes (5 days) with 28.63 effective bright sunshine hours. The maximum internal temperature of the dryer was 27.1°C above ambient, the minimum internal humidity was 30% below ambient and the average efficiency was 19.20%. The results demonstrated the dryer to be efficient, low cost and controlled in humid tropical environment.

Mankani *et al*., [21] study examined the drying of newly harvested crops with two types of commercial sun dryers, a box-type hybrid energy solar dryer (T1) and a convective solar dryer (T2). In a field of a farmer in Kurtakoti village, Karnataka, India, Byadagi red chili beans were dried in two methods, i.e., regular tarpaulin drying (T3) and drying on the earth (T4). The box type hybrid dryer was operated by a 50 W solar PV panel to run six exhaust fans, with an optional domestic electrical connection to operate the fans; the convective dryer was made of galvanized iron with a detachable frame, three perforated trays, a polyethylene cover and a 40 W exhaust fan powered by PV. T1 demonstrated total drying in 4 days with 0.90% w. The box-type hybrid solar dryer obtained 2.40 kg

/day MRR moisture content and is improved as compared to T2, T3 and T4. The regression investigation revealed that the box type hybrid solar dryer is more efficient, dries uniformly and protects the quality as the moisture content decreases linearly with increasing insolation.

Pagar *et al*., [22] did a comparative study on an indirect solar cabinet drier (SCD) and a direct solar tunnel dryer (STD) for drying of tomato slices (4 mm thick) under environmental circumstances in Nashik, India. The SCD consists of a collector, drying chamber with four trays and a tiny fan for airflow, whereas the STD comprises of two series-connected tunnels with four trays in each and a rectangular opening to enable hot air circulation, under forced convection mode. The experimental results indicated that the STD dried the moisture content from 80% to 15% in 12 h while the SCD took 19 h with higher drying air temperatures (up to 63 °C), better moisture removal rate, and average drying efficiencies of 29–30% compared to 14–17% for the SCD, which confirms that the forced convection solar tunnel dryer provides faster drying, better air circulation, and improved quality dried tomatoes for smallholder farmers.

Tibesso *et al*., [23] developed and tested a polyhouse type solar dryer for drying of wet coffee and hot pepper in Jimma, Ethiopia. The dryer is designed in the shape of a semi-circular tunnel of 5 m length and 2 m width, consists of a solar collector, a drying chamber and an air distribution system with chimney and is composed of UV-stabilized transparent plastic film and locally available materials like as plywood, aluminium sheets and wire mesh. The experimental results showed that 150 kg of hot pepper was dried from initial moisture content of 82.95% to 10.42% in six days, 50 kg of wet coffee from 51.89% to 11.10% in three days and the average internal temperatures was found to be in the range of 53.90°C to 62.57°C for hot pepper and 50.08°C to 54.08°C for wet coffee. The relative humidity inside the dryer was consistently lower than the ambient humidity. The thermal efficiencies were 86.87% and 64.48% for hot pepper and wet coffee respectively. These results indicate the effectiveness of the dryer, short drying time and suitability for smallholder farmers.

1.2.2 Indirect solar dryer

Kilanko *et al*., [24] developed and evaluated a natural convection sun dryer for scotch bonnet pepper with an overall dimension of 1000 mm × 410 mm × 700 mm. The drying chamber was insulated with aluminum foil and the solar collector was made of gavanized sheet with top glass panel of 800 mm x 380 mm with air flow based only on natural convection. The trials conducted during 2 periods of 3 weeks showed an average reduction of 81.3% w. b. of moisture starting with 200 g of pep-per with an average efficiency of 28.4 % of drier. Results indicated that spontaneous convection solar drying can be an effective strategy for food preservation and reduction of post-harvest losses in tropical circumstances.

Hossain *et al*., [25] developed, built and analyzed an indirect solar-powered vegetable dryer for preserving red amaranth, moringa, and coriander leaves. They employed locally available materials such as wood, glass, aluminum and galvanized steel wire trays. The dryer consists of a solar collector, drying chamber with three trays, axial inflow fans, exhaust fan and a 50 W solar PV system to run the fans. Drying temperatures of 51–57°C were attained compared to ambient temperatures of 29–35°C. At the end of four hours, the experimental results indicated moisture de-creases of 36.11%, 25% and 15% for red amaranth, moringa and coriander leaves, respectively. The drying efficiencies were in the range of 34.67–39.08% with better color retention and the payback period of 0.78 years showing that the system is successful, cost effective, and suited for small-scale farmers in Bangladesh.

A Modified Active Solar Dryer (MASD) was designed, fabricated and tested for drying of chili in Pakistan and its performance was compared with that of a Simplified Active Solar Dryer (SASD) by Meghwar and Kumar ,[26] The MASD is composed of a flat-plate thermal collector with black-painted

L-type aluminum fins, a rectangular drying chamber (0.45 × 0.30 × 0.45 m), two DC fans at the input and one at the out-put for pumping the heated air, and a stand angled at 25° to improve the solar irradiation . The test findings indicated that the MASD had a higher drying temperature (69°C) than the SASD (59°C). The drying time was 34 hours for drying from 80% to 10% moisture as against 45 hours in SASD and the product was dried in 2 days in-stead of 5 days. MASD was faster in drying with better quality retention and suitable for small scale agricultural application under the controlled temperature setting.

Hussain *et al*., [27] designed and experimentally evaluated indirect sun tunnel drier for drying apricot in Northern region of Pakistan. The drying was carried out in a tunnel dryer of 10 m x 1.22 m. It had a solar collector, drying chamber and three 2.5 W DC fans powered by a photovoltaic module. The Computational Fluid Dynamics (CFD) simulation, by using SolidWorks flow software, predicted the air flow velocity of 3 m/sec at the collector and 2 m/sec at the drying chamber, and the temperature distribution of 350 K at the collector and 335 K at the drying chamber. The experimental validation revealed that the average temperature difference between models and observations was as little as 1.5 °C. The dryer was found to reduce the moisture content of apricots from 80% to 15% in 10h compared to 3 days in open sun drying with collector, and the overall dryer efficiencies were 45 and 29% respectively, showing efficient, hygienic and uniform drying of apricots under controlled solar assisted drying conditions.

Bharadwaz *et al*., [28] devised, constructed and evaluated an indirect forced convection solar dryer for drying of agricultural products using green apple slices as a model product. The system consists of a flat plate solar collector (1.7 × 1 m2) with a black painted galvanized absorber plate, four baffles to create non-linear airflow and to raise the temperature of air, a drying cabinet (146 × 100 × 60 cm) made of seasoned wood and a 210 W, 2800 rpm centrifugal air blower to force the heated air through the drying chamber. Experimental trials were conducted for the months of March and April between 9 am and 4:30 pm to find out the temperature inside the drying chamber which reached 51°C with the relative humidity being much lower than the ambient and the solar dryer removing more moisture (164.2 g) than open sun drying (155.4 g). The chemical analysis revealed the crude protein (3.32% vs 2.78%) and dry matter (83.17% vs 82.52%) contents were greater in the solar dried samples. The characteristics included better preservation, faster drying and cost effectiveness using locally available materials.

Elwakeel *et al*., [29] developed a photovoltaic powered sustainable forced convection solar drier (SFCSD) for drying five varieties of date fruit (Shamia, Bartamuda, Sakkoti, Malka-bii and Gondaila) in Aswan, Egypt. The system includes a flat plate solar collec-tor of 3 m2 , drying room of 1 × 0.45 × 0.98 m with nine perforated trays placed at a spacing of 11 cm. Glass cover of 3 mm thickness, galvanized metal frame and an AC suction fan of 220 V and 50 W rating. The SFCSD has two modes of operation. Forced air circulation (active) and natural air circulation (passive) are used based on the interior air temperature and the ambient light intensity. It integrates with sensors for temperature, relative humidity, light intensity and fan speed and an SMS based early warning system. The initial moisture content of date fruit ranged from 10.32-12.56% and it gained equilibrium in nine days. Effective moisture diffusivity was obtained in the range of 3.5569 × 10-7 m2/s and 3.9489 × 10-7 m2/s. The maximum efficiencies of PV system and solar collector were obtained as 25.28% and 69.52%, respectively. Environmental assessment demonstrated that so-lar drying is a sustainable, efficient and reliable solution for date fruit with an energy payback time of 7.15 years, a CO2 mitigation of 93.2 tons and generated carbon credits of USD 6,757 over a projected lifetime of 30 years.

Elwakeel *et al*., [30] examined a modified solar dryer with automatic solar collector tracker (ASCT) for drying tomato slices in Luxor City, Egypt. It comprised of a flat-plate solar collector, a drying chamber, a suction fan driven with a 75 W PV system, and an IoT-based tracking control tracking the sun's position to maximize the absorption of solar energy. Experiments were conducted for the thickness of 4, 6 and 8 mm with 1.0, 1.5 and 2.0 m/s air velocities. Results showed that the ASCT-enhanced dryer improved the internal air temperature (~18%) compared to the fixed solar collector (FSC), reduced drying time and improved product quality in terms of final moisture content, total phenols, ascorbic acid, pH, color, acidity and rehydration ratio. Slices of 8 mm at 1 m/s yielded the highest rehydration ratio, 4.43 kg water/kg dry matter. The study shown that the inclusion of ASCT increases the thermal efficiency and the product quality in solar drying operations.

Simate *et al*., [31] built a natural convection solar tunnel dryer of total size 5.0 m 2 and capacity of 114.2 kg for drying maize ears. The dryer is composed of plywood and UV stabilized greenhouse plastic and has a vertical flat-plate solar chimney to boost buoyancy-driven airflow. The experimental experiments showed that the dry-er could reduce the moisture content of maize from 23.4% to 12.5% in 5 days while open sun drying took 12 days. Temperature and airflow distribution were studied using CFD models, and exergy analysis was utilized to find irreversibility losses and options for increasing chimney height. The payback period of 3.7 years confirmed the economic viability of the system and it is a feasible sustainable solution for smallholder farmers.

1.2.3 Mix solar dryer

Moywaywa *et al*., [32] developed and fabricated a mixed-mode solar dryer for black soldier fly (BSF) larvae. The dryer has a solar collector, a drying chamber with three trays placed vertically one above the other, a transparent canopy, and airflow con-trolled by natural convection. The highest solar radiation intensity of 833 W/m2 around noon resulted in the maximum drying temperature of 61°C, with the solar collector showing maximum efficiency of 57.58%, and the BSF larvae sample of 750 g was dried to a constant mass of 302 g. The drier achieved uniform drying without contamination, reduced the moisture content from 60% to 49% in 8 h and achieved dryness in three days. It was an efficient low-cost sustainable solution for drying BSF larvae.

Khalif and Jabr [33] designed and constructed a Smart Hybrid Solar Dryer (SHSD) and a regular hybrid solar dryer (HSDT) for drying of medicinal plants such as peppermint, rosemary and sage. Temperature and humidity of the drying chambers were regulated using sensors and fans. The study was conducted for air discharge angles of 40°, 70° and 90°. The maximum solar collector efficiency of 51.44% was achieved by the SHSD at air discharge angle of 40° and maximum volumetric air flow of 0.030 m3/s at air discharge angle of 90° which reduced the energy loss and increased the drying performance as compared to the HSDT. The SHSD system pro-vides higher quality dried herbs, faster drying time, better energy economy and more operational flexibility. The efficiency of the SHSD system is proven for small and medium scale applications.

Hailu [34] designed and constructed a solar tunnel dryer for drying ginger at Bahir Dar University. The dryer consisted of a tunnel of 8.5 m long and 2 m wide with a triangular cross-section. The total area of the solar collector was 8 m 2 and the dry-ing chamber was 11 m 2. Two small axial fans powered by a 50 W PV module were used to provide the airflow over the product. Experiments were conducted with 8 kg of sliced ginger under no-load and full-load conditions. The dryer reduced the moisture content from 90.4% to 11.9% (wet basis) in 24 hours as against 40 hours for open sun drying, and maintained the product quality and protected the ginger from rain, insects and dust. The solar tunnel dryer had a drying efficiency of 31.6% with air temperatures of 77.9 °C at the collector output. A net saving in drying time of 40% was realized showing the solar tunnel dryer to be a low-cost sustainable solution for small-scale farmers.

Peratheepan *et al*., [35] devised and developed a solar tunnel drier with an auxiliary flat-plate solar air heater for drying bitter gourd (Momordica charantia). The dryer consists of a collector chamber and a drying chamber separated by a perforated board of MDF. The drying chamber is equipped with a tilted platform and a corrugated aluminum roof covered with UV-stabilized semi-transparent polyethylene. The air heater is a V-grooved galvanized absorber plate insulated by wood dust and covered by a glass plate. The results from the experimental study showed that the system with the auxiliary heating unit achieved higher temperatures and better uniformity of drying (average interface and outlet temperatures of 68.3 ° C and 64.7 ° C respectively) as compared to the dryer without the auxiliary unit (51 ° C and 49.9 ° C respectively) and the moisture content was more effectively reduced with better moisture removal and effective moisture diffusivity as compared to open sun drying to demonstrate the effectiveness of the hybrid solar tunnel system .

Chavda *et al*., [36] conceived, developed and demonstrated a shallow solar tunnel dryer of 21 m2 for agro-industrial products in non-electrified areas. The system is modular, consisting of three units: air heating unit, drying unit, and air diversion unit, covered with UV-stabilized plastic sheets. The airflow from heating to drying zone is through six DC fans powered by solar PV modules. The drying tests showed that 26 kg of green chillies were dried from an initial moisture content of 87% to a final moisture content of 10% (wet basis) in a time period of two days, resulting in a drying rate of 1.73 kg/h with a collector thermal efficiency of 26%. Peak temperatures in the drying tunnel reached 67.4 °C. The system was shown to operate efficiently and independently of the grid making it suitable for remote areas.

Akter *et al*., [37] conducted a study on the performance of a solar tunnel drier for drying cabbage at the Advanced Drying Lab of Bangladesh Agricultural University and compared its performance with open sun drying. The system is composed of a metal frame, collection and drying units with a plastic coating, a wooden net tray and three DC fans fed by a 50 W photovoltaic module that produces an airflow along the east-west oriented tunnel to optimize the exposure to sun radiation. The experimental results revealed that the moisture content decreased from 94.42%, 90.18% and 92.24% (w.b.) to 4.85%, 15.84% and 15.71% (w.b.) in 28, 21 and 19 hours for three trials. The drying rate and efficiency of the solar tunnel dryer were 0.15 kg/h and 8.22% respectively compared to 0.02 kg/h and 3.38% in open sun drying. The color and texture of the dried cabbage were better than open sun drying. The system was effective, suitable for low temperature and has a good potential for rural agricultural applications.

Manvi and Shriramulu [38] constructed a forced convection mobile solar tunnel drier with a batch capacity of 60 kg for drying fresh silkworm pupae, measuring 6.58 × 1.8 × 1.1 m (L × W × H) and having a mild steel square tube frame covered with 5 mm thick toughened glass. The dryer is composed of a solar collecting section (6.48 m²), a drying section (4.32 m²) with four perforated trays, and an exhaust section with three 11.5 cm axial DC fans powered by a 20 W solar photovoltaic panel to re-move damp air and to provide forced air circulation. Experiments showed that the dryer could reduce the moisture content from 103.32–145.45% (d.b) to 8.72–9.97% (d.b) in 7.5–9.0 h, achieving a maximum internal temperature of 95.6°C at an ambient temperature of 36.2°C, with a 25–30% reduction in drying time and better chemical quality than open sun drying. The results demonstrated an efficient, low-cost and mobile operation suitable for sericulture by-products.

Deepak and Behura,[39] undertook a thermodynamic sustainability and environ-mental analysis of a mixed-mode solar tunnel drier with sensible heat energy stor-age (SHES) and latent heat energy storage (LHES) for drying of Cucumis sativus slices in Vellore, India. It has a drying chamber of 1.9 m × 0.9 m made of UV-stabilized polycarbonate sheets on a hemispherical mild steel frame, two wire mesh trays, a flat-plate solar collector of 2.04 × 1.06 m with a centrifugal blower of 250 W at its inlet and energy storage units comprising 20 kg black pebbles (SHES) at the base of the dryer and 4 kg lauric acid PCM (LHES) in a trapezoidal chamber at the collector outlet. The experimental results in three cases (without energy storage, with only SHES, with SHES + LHES) showed that the drying time decreased by 25% with addition of SHES and it decreased by 50% with combination of SHES + LHES and achieved maximum energy efficiency 14.2%, average energy efficiency increase 53% and maximum collector energy efficiency 84.6%. The results of the exergy analysis showed that the dryer has a maximum exergy efficiency of 51.3% and an average exergy efficiency of 34.3%. The study also provided environmental benefits with a potential of CO2 mitigation of 83.97 tonnes/year and a short payback period of 1.82 years for the combined energy storage case focusing on increased productivity, energy utilization, and sustainability for solar drying applications under different irradiance conditions.

There have been several studies on solar tunnel dryers, however the literature is scattered about different designs, operating conditions, and performance parameters. In addition, there is lack of comprehensive comparison of direct, indirect and mixed-mode systems in terms of efficiency, drying performance and sustainability. Hence, a thorough assessment is necessitated to systematically analyse and evaluate present developments and to identify the significant research gaps and future enhancements. The objective of this research is to comprehensively analyze design, performance and sustainability of solar tunnel dryers in order to evaluate and find the most appropriate configurations for smallholder farmers.

2. Methodology

This evaluation was carried out by conducting a complete analysis of published scientific studies connected to solar tunnel dryers. The literature was reviewed from several research sources such as Google Scholar, ResearchGate, and other scientific websites available in the internet. The search procedure was focused on studies relating to solar tunnel dryer design, their thermal performance, drying efficiency, energy consumption, economic feasibility and sustainability. The selected studies were examined and grouped according to the kind of dryer, which included direct, indirect and mixed solar dryers, and natural and forced convection systems. Performance metrics mentioned in the literature such as drying time, thermal efficiency, moisture content reduction, product quality and environmental implications were also compared and studied. Then the findings were summarized to find out recent breakthroughs, advantages, limitations and future research trends in drying technology employing solar tunnel dryers.

3. Result and Discussion

In all the studies which were conducted, solar tunnel dryers always performed bet-ter than open sun drying. As reported by Mohod *et al.*, [11,12] the reduction in drying time was 28% for fish, 57.14% for grapes as reported by Palled *et al.*, [17], and 30–50% for tomatoes, maize, and mangoes as reported by Ujunwa *et al.*, [16]. These differences indicate the effect of product type and dryer setting on the drying efficiency. The thermal performance of the various designs varied significantly. Sookra-moon [13] reported a thermal efficiency of 22.72% for rice drying, while for date palm drying, Poonia *et al.*, [19] reported an efficiency of 36.6%. In addition, Deepak and Behura, [3] pointed out the large contribution of thermal enhancement techniques, in which 53% of energy efficiency was obtained by adding heat storage devices. Also moisture content was successfully reduced to appropriate storage levels in all studied tests. Hussain *et al.*, [27] reduced the moisture content of apricots from 80% to 15% in 10 hours in comparison to 3 days taken for open sun drying. Tibesso *et al.*, [23] reduced the moisture content of hot pepper from 82.95% to 10.42% with thermal efficiency of 86.87%. The results validate the improved drying kinetics of solar tunnel dryers. In addition, indirect and hybrid types of solar dryers generally produced better product quality retention.

Bharadwaz *et al*., [28] reported more protein retention while Elwakeel *et al*., [30] reported better color and ascorbic acid content i.e. better nutritional and sensory quality than conventional drying methods. Furthermore, economic evaluations proved the feasibility and economic benefits of solar tunnel dryers in different geographies and scales. Payback timeframes were from 0.78 years [25] to 3.7 years [31], but benefit–cost ratios were generally more than 1.0. The results show solar tunnel dryers are a low-cost, sustainable and adaptable post-harvest technology for smallholder farmers in developing countries.

4. Conclusions

This review evaluated the design, performance and sustainability of solar tunnel dryers for drying of agricultural products. Results indicated that the use of solar tunnel dryers instead of open-sun drying significantly reduced the drying time, improved the product quality, and reduced the risk of contamination. Forced convection, indirect and hybrid approaches give more uniform drying conditions and increase thermal efficiency. The economic results reveal high profitability and short payback periods which are suitable for small and medium agricultural producers. These techniques will result in less use of fossil fuels and encourage sustainable post-harvest processing. The results confirm that the objectives of the review have been achieved in relation to performance, economic viability and sustainability. Further research is recommended to refine design parameters and assess performance under a range of environmental situations and at bigger scales.

5. Recommendations

1. Help for smallholders: Building a portable, low-cost solar tunnel dryer from materials that are readily available in the area to allow smallholders and rural populations to use it in their production.
2.24 hour operation thermal storage: phase change materials (PCMs) and other real or latent heat storage technologies can be utilized to continue the drying process at night or in the absence of bright sunshine
3. Environment monitoring: methods to cut carbon emissions need to be assessed periodically to ensure they will work in the long run and help the environment the most.
4. Smart control systems: Use of sensors for temperature and humidity in automat-ed control systems will help to improve and accelerate the drying process.
5. Mixed Designs: Development of combined direct/indirect sun drying systems with the possibility of an additional heat source as needed. This aims to improve temperature stability, reduce drying time, and optimize air distribution within the dryer.

Acknowledgement
This research was not funded by any grant

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