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# Solar Ddryers for Food Preservation: An In-Depth Review of Design, Fabrication and Barriers

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**Abstract**
Processing of food should adopt an energy efficient path such as renewable energy, instead of conventional energy intensified units. Solar energy is one such option, which is cost effective and energy efficient. But developing a cost-effective solar product with optimised design factors to produce premium quality food is bit challenging. The solar components are to be designed and selected to attest to maximum utilisation of solar energy and its conversion. The review is structured into five parts. The first part explores the different types and limitations of solar dryer, the second part focuses on various design and fabrication aspects of each and every component of a solar dryers, the third part focusses on selection criteria, fourth part elaborates on the environment, economic and social aspects of solar dryer and fifth part focusses on challenges and future prospects. SWOT analysis of various types of solar dryer is also presented in this work. Upgrading solar dryers with modern technologies for maximum efficiency with distributed production and feasibility of drying multiple food products, will yield higher payback. However, the quality of dried food, especially the aroma and nutrition value will significantly affect the revenue generation.

**Keywords** Solar dryer · Collector · Absorber · Reflector · Challenges

**Abbreviations**

| | |
|---|---|
| ASD | Direct solar dryer |
| ISD | Indirect solar dryer |
| SH | Sensible heat |
| LH | Latent heat |
| PCM | Phase change material |
| MMASD | Mixed mode active solar dryers |
| SWOT | Strength weakness opportunity threats |
| HP-ETSC | Heat pipe evacuated tube solar collector |
| HAGSD | Hybrid active greenhouse solar dryer |
| PVTC | Photovoltaic thermal collector |
| CPC | Compound Parabolic Concentrator |
| ET | Evacuated Tube |
| IRR | Internal rate of return |
| NPV | Net present value |
| $h_c$ | Convective heat transfer coefficient |

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## Introduction

Abundance of energy is available from sun and can be used free of cost. Burning of fossil fuel has time and again proved to be harmful and hazardous for the environment as well as human health. Power generation through solar energy which is one of the renewable energies, promises clean power along with reduction in carbon footprints and greenhouse gases [1]. In ancient times food grains were dried under across the globe. Direct sun drying depends upon the weather conditions. Prolonged exposure to sun reduces the nutritional value and thus decreasing the quality and quantity of the food stuff. Radiation of the sun is partially absorbed while drying directly beneath the sun [2]. To use solar energy efficiently, the incident radiation must be concentrated and converted into thermal energy. Solar dryer facilitates the use of the lost incident radiation in an effective way. Through the use of a collector, the incident solar radiation is focused.

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The radiations pass through the collector and strike the absorber surface which is painted by a selective coating. The temperature of the absorber rises and the air passing through it carries the heat through convection, to the solar drying chamber where the food stuff is placed [3]. The hot air removes the moisture from the food stuff through diffusion. Countries and places having extreme climates can dry fruits and vegetables when they are available in abundance and can use it throughout the year. Solar driers can control the taste and quality of dried stuff, increasing the product shelf life [4]. It is having an edge over the conventional dryers in terms of maintenance and operational costs. There are several solar dryers which are designed for maximum thermal efficiency. Most of the previous review works are limited to performances of a solar dryers. The present work demonstrates, in-depth review on various types of solar dryers along with their design and fabrication details and the challenges involved. The review navigates through following objectives.

a) Types of solar dryer highlighting their constructional features and limitations
b) Design and fabrication of different components of a solar dryer
c) Environmental, economic, and social aspects of solar dryer
d) Challenges and future scope

## Types of Solar dDryer

Based on the mode of drying, solar dryer can be classified as a) Passive dryers and b) Active dryers Fig. 1

## Based on Air Movement

### Passive Dryers

The radiation is penetrated through the transparent cover and falls on the food stuff. A Greenhouse effect and thermosyphon effect, induces natural air circulation inside the dryer [5]. Passive solar dryer is best suited to dry greens in small batches. Passive solar dryer are indirect and direct type. The capacity of the dryer is increased by installing vertical racks or trays inside the available area. A draft force is created by installing a chimney in the drying cabinet, which creates a vertical flow of air in the cabinet [6]. Some passive dryers are incorporated with a chimney or stack and also energy storage device to utilize the energy during night times [7]. These types of dryers are characterised by low energy cost and effective drying, without compromising on mass loss and quality of dried products. Minimal expenditure is incurred in drying the food products.

### Active Dryers

Active dryers use external source to heat the air to a higher temperature. They are classified as direct active solar dryers, indirect active solar dryers and mixed mode active solar dryers. In case of active solar dryers, the air circulation is regulated through a fan or blower which in turn increases the heat transfer rate. These solar dryers are used for crops or vegetables with high moisture content and which require low temperature solar drying (Fig. 2).

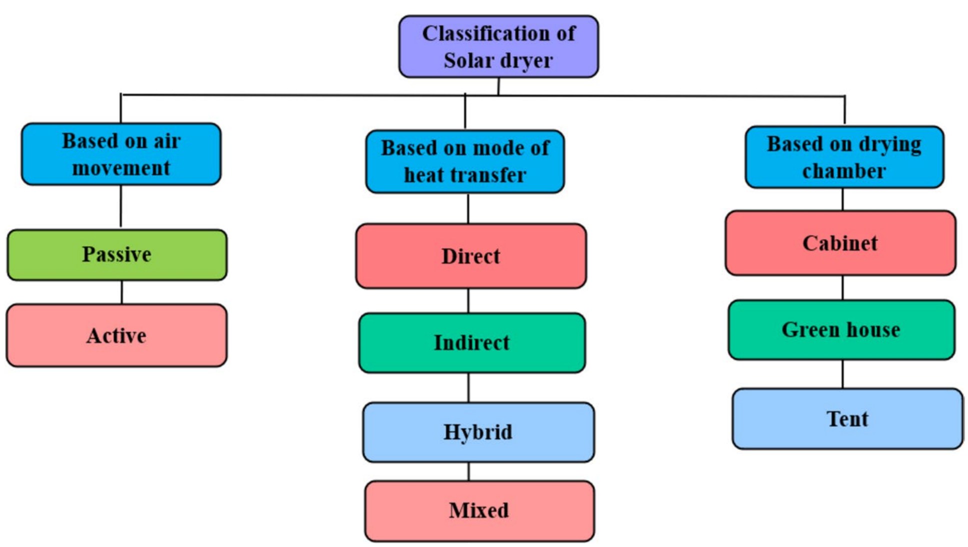



**Fig. 1** Classification of solar dryer [1]


**Fig. 2** Direct solar dryer [7]

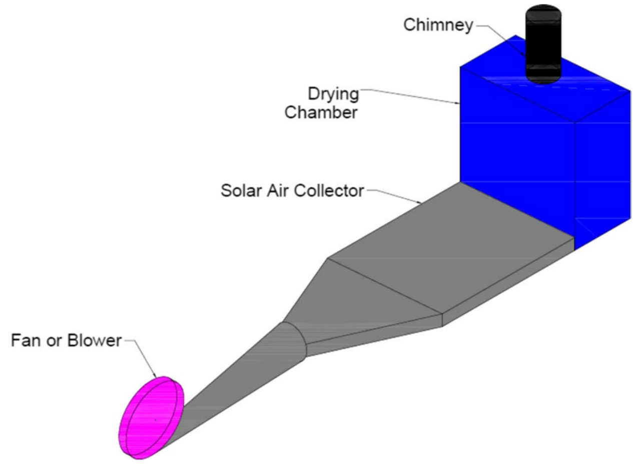



**Fig. 3** Indirect solar dryer [11]

## Based on Mode of Heat Transfer

### Direct Solar Dryers

DSD consist of a fan or a blower. Air can be forced or induced through a fan at inlet or outlet. Continuous operation of the fans requires electricity, which results in higher operating costs. The drying chambers are constructed like a dome or tunnel. The drying chamber is surrounded by a transparent plastic film [8]. The drying chamber consists of perforated trays to facilitate air circulation through the trays. The shorter wavelength radiation passing through the transparent cover is converted into longer wavelength radiation. These long wavelength radiations are unable to pass through the transparent cover again and hence the low-grade heat is conserved in the drying chamber [9].

### Indirect Solar Dryers

ISD consists of a fan or blower at the entry point of the air as shown in Fig. 3. This method is significant in maintaining the nutrition value and colour of the dried food stuff [10].

Two crucial factors for effective drying of food are sunlight and climatic conditions. With an additional unit connected to the drying system, the process parameters can be better regulated and the heated air can be used even under adverse conditions [11]. The auxiliary units can be renewable or non-renewable.

### Hybrid Solar Dryer

Figure 4 depicts the detail classification of the indirect solar hybrid system with renewable and non-renewable assisted systems.

The hybrid type solar electric dryer consists of an auxiliary heating system such as resistance heaters to heat the air in addition to the heat absorbed by the solar collector [13]. This type of system is used during periods of low irradiation. If the air temperature of the collector is not sufficient for drying, thermostatically controlled resistance heaters are used, Fig. 5. Electric heaters are a promising additional energy source that increases the heat density, but is also associated with costs. A chemical heat pump is used to heat the air with the exothermic reaction as shown in Fig. 6. In general, reactions that are reversible and can be regenerated using solar energy are preferred [14].

The heat pump regulates the drying temperature and humidity and also saves energy [15]. The heat pump can absorb LH and SH together with the dryer. It saves 40% energy compared to electric heaters [16]. The dehumidification process is used to increase the moisture removal rate from food [17]. This type of system is very effective in humid areas or coastal areas. Dehumidification is done using a refrigerant such as ammonia. The process includes adsorption and desorption, with the adsorption stage lowering the temperature in the evaporator as liquid ammonia is converted into gas. At the same time, heat is released when gaseous ammonia and solid react at high temperatures. This process is generally applied at the entry point of the dryer. A part of the exhaust air is redirected to the evaporator and is cooled and dehumidified. The cooled and dehumidified exhaust air is again heated by a condensed refrigerant in the condenser. Solar dryer with thermal storage system accumulates the heat during sunshine period and releases heat during night time [18, 19]. The thermal energy can be stored in form of SH or LH. The PCMs are used for storing LH whereas solid (rock), liquid(water) or organic solvents like butanol, propanol octane etc. is used). PCM will have high energy storage density at constant temperature. Choosing the correct storage material and evaluating the heat storage capacity is a crucial aspect of this type of solar dryer.

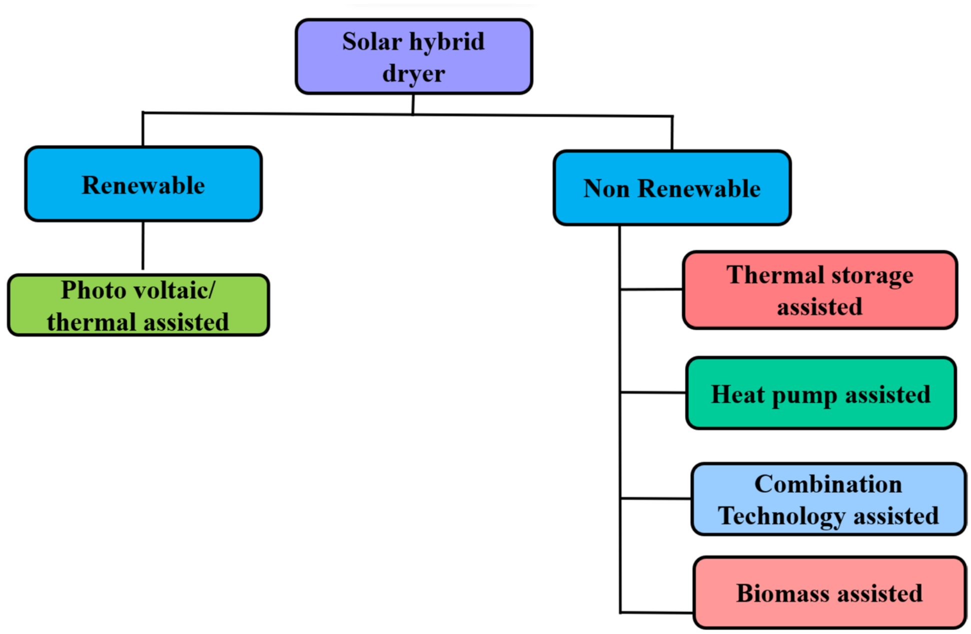



**Fig. 4** Classification of solar hybrid dryer [12]

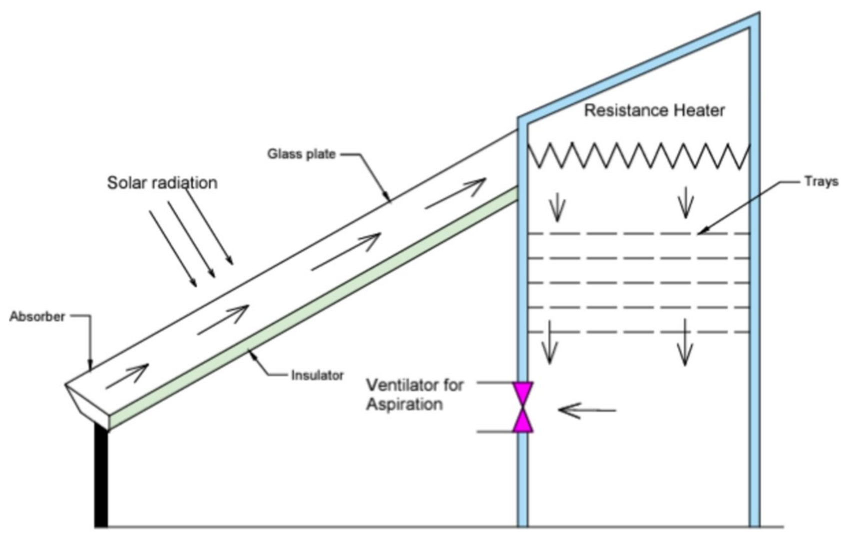



**Fig. 5** Hybrid solar dryer with resistance heater [13]

### Mixed Mode Active Solar Dryers

**MMASD incorporates fan/blower** Fig. 7**.** The blower can be powered by either a solar photovoltaic panel or electricity.

## Based on Drying Chamber

### Cabinet Type dryer

In Cabinet type dryer the food items are placed inside metal box or wooden box which is well insulated to prevent the heat losses[6]. The cabinet receives direct radiation through the glass cover and warm air is also passed through the drying chamber and the trays through the duct. This combined action provides necessary heat for the food products to loosen moisture. Cabinet dryers are used for low or moderate scale.

### Greenhouse Solar Dryer

A greenhouse dryer is a system designed to dry crops or agricultural products using the controlled environment of a greenhouse. By utilizing natural sunlight and maintaining optimal humidity and temperature levels, these dryers can effectively reduce moisture content from the produce. Greenhouse incorporates openings, to allow airflow, which helps in moisture removal [7]. It can be used for a variety

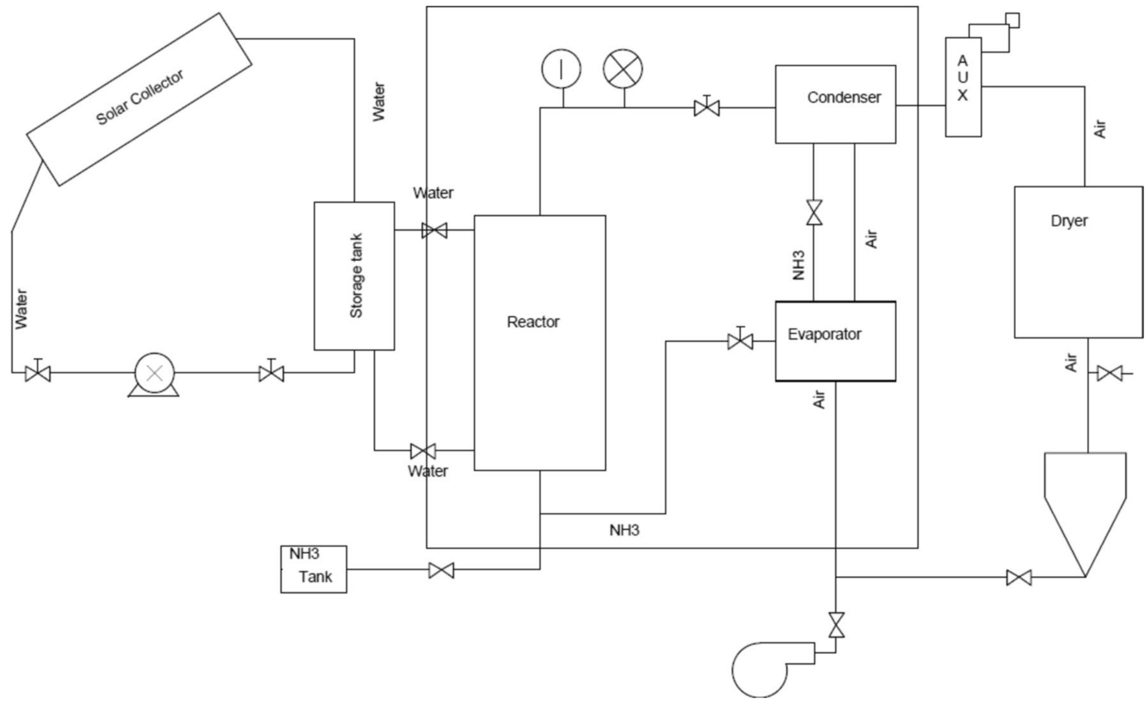



**Fig. 6** Hybrid solar dryer with chemical heat pump [14]

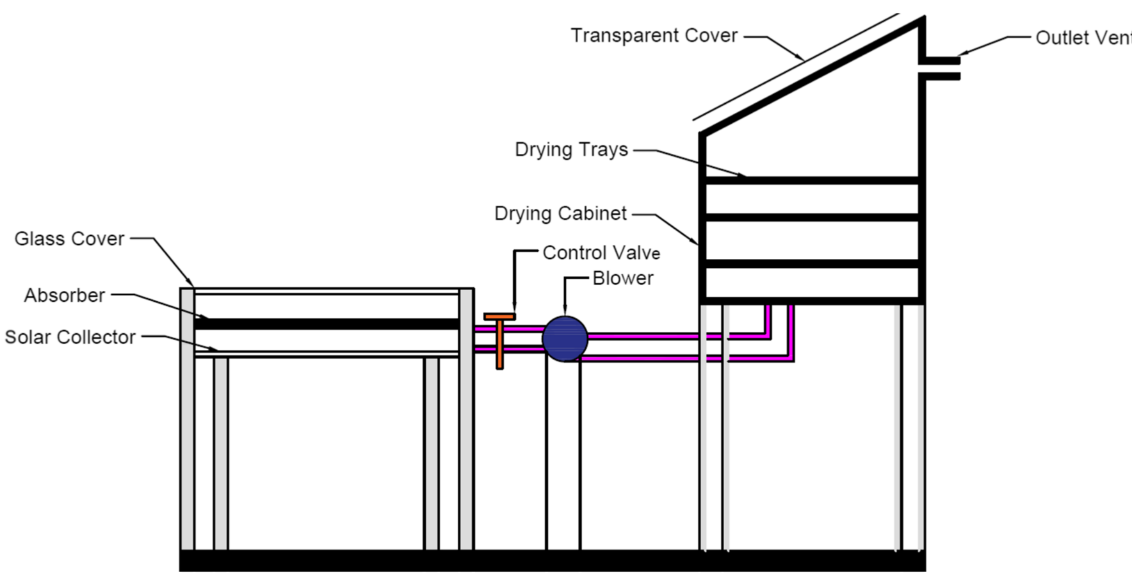



**Fig. 7** MMASD [20]

of crops, making it useful for small-scale farmers as demonstrated in Fig. 2.

### Tent Type Dryer

Direct and indirect solar dryers are both possible for tents. The dryer has trays, a concrete base, a chimney, and structure. A dome, triangle, or flat top can be used for the structure. The structure can have a polythene sheet covering it and be constructed of metal or wood. There is a sheet of black polyethene on the ground. There are two varieties of solar tent dryers: does and kanji. A transparent polythene tent, wooden frames, a drying rack, a zip, black igneous rocks, and a mosquito net are all included in the Kainji Solar tent dryer. Figure TEN [24] shows how these tent dryers can also be integrated with mixed mode. Direct heat received through the polythene and indirect heat received from the air from the collector increases the overall drying efficiency of the produce. The temperature rises as a result of solar energy entering the tent through the polythene sheet and becoming trapped there. The produce on the rack loses moisture as a result of the cool air that is forced into the tent from the openings. Table 1 summarises the strength weakness opportunities and threats of different types of dryers.

## Design and Fabrication Perspective of a Solar Dryer

Solar dryer comprises of an absorber, a collector, drying chamber and an insulator. To provide premium quality products, many researchers have tried several designs to enhance the performance of the dryer. The following section discusses about different designs of each component of solar dryer.

### Collectors

#### Stationary Collectors

The primary function of solar drier is to gather the beam radiation and transform it into thermal energy. Solar beam is collected through a glazing cover which allows the radiant energy to pass to the collector. The radiations strike the black surfaces, get absorbed and convert into heat. With a good absorber material, most of the incident radiation is absorbed and very less gets reflected back. Solar collectors can be a flat plate, line focus or point focus collectors. A detail classification of solar collectors are given in Fig. 8

#### Flat Plate Collectors

These collectors are of common choice of researchers as it is economical and easy to fabricate [23]. Generally Galvanised Iron sheets are used for collectors as they are good conductors of heat and painted black for maximum absorptivity. The thickness is maintained between 0.6 to 0.8 mm. Flat plate collectors can be with double pass air flow passages with absorber plate as a separator [24]. Flat plate collectors are also used in solar mixed mode dryer. In mixed mode dryer, the moisture removal occurs by direct beam radiation incident inside the chamber as well as through the heated air which is passed through the collector which is either natural convection or forced convection as shown in Fig. 9.

Forced convection MMASD consists of glass cover, absorber (G.I sheet), blower and base plate along with solar air collectors. Basically, solar air collectors are double pass counter flow or single pass [25, 26]. Solar collectors can also be coupled with small scale greenhouse dryer as shown in Fig. 10. The combined effect of beam and the heated air through the collector, provides average temperature of 60 °C–65 °C which is enough for drying sea products like fish [27].

**Evacuated Tubes** With flat plate collectors, controlling the parameters and effective harnessing of solar incident radiation during cloudy day is a bit challenging task [28]. ETSC have better efficiency than flat plate collectors [29, 30]. Tubular absorber with selective coatings ensures good performance during lower radiation period [31]. The vacuum between the two tubes ensures minimum conduction and convection losses [32], and in case of breakdown of one of the tubes, no need to stop the whole system [33]. Detailed classification is given in Fig. 11.

Solar dryer based on HP-ETSC with reflector was designed and fabricated by [35]. The collector consisted of number of evacuated tube collector (ETC) tubes with heat pipe connected to manifold made of copper. The manifold was insulated with glass wool to prevent the thermal losses Fig. 12.

The performance of ETSC can be increased, if PCM material is used for energy storage[ [37, 38]. The capability of drying process increases with PCM [36, 40]. The inlet air can be preheated with parallel arrangements of ducts connected to the collector [39]. Evacuated tube solar collectors are available in different configurations. U-Tube configuration involves less complexity of design and fabrication with high practical features [41]. Parallel type evacuated tubes in combination with nano fluids, is used for drying agricultural products as shown in Fig. 13 [42]. Addition of nanofluids is a promising solution for solar collectors with variations in its particle sizes and morphologies. Thermal efficiency can be improved with sets of evacuated tubes with tube in tube arrangement. Inner tubes can be coated with selective coatings and outer tube can be transparent. The beam radiation incident on the transparent glass tube heats the absorber tube. Addition of nano particles like $Al_2O_3$ to the fluid flowing inside the absorber tube increases heat transfer rate.

HP-ETSC combined with a heat extraction system, harnesses the sun's maximum radiant energy and increases the overall efficiency of the dryer [43, 44]. Heat from the hot water flowing in the tubes is extracted by the air flowing over it Fig. 14.

Solar dryer with ETSC is suitable for crops or food stuff with high moisture content. The use of heat exchanger increases the average temperature resulting in increased drying rate [44] as shown in Fig. 15.

Solar drying can be coupled with PVTC (Photovoltaic thermal collector) as shown in Fig. 16. However, results

**Table 1** Strength weakness opportunity threats of different categories of dryers

| Type of Solar Dryer | Strength | Weaknesses | Opportunities | Threats |
|---|---|---|---|---|
| Passive dryers [21] | • Economical and does not need skill ed assistant | • Doubtful quality of dried products and large space required<br>• Frequently food stuff is subjected to over drying<br>• Non uniform drying | Can be used for rural households | • Rodents, birds, insects and animals can spoil the product as it is kept open in space<br>• Climatic conditions like rain and dew drops can affect the quality of food stuff<br>• Often microorganisms are formed on the surface of the food<br>• Food is spoiled due to dust and pollution |
| Active solar dryers [22] | • Closed enclosure ensures improved product quality<br>• Subjected to less contamination<br>• Less costlier than indirect type solar dryer | Direct exposure to beam radiation, degrades the quality of food stuff | Can be used for small capacity | • Since the food stuff is dried in closed enclosure, condensation occurs on the surface of the glass and glass looses its transmissivity<br>• Frequently the glass needs to be changed |
| Direct solar dryer [8] [9] | • Cost effective<br>• Simple deign<br>• Can accommodate small and large | • Variable efficiency<br>• Drying capacity is less | • Increasing market for sun dried products | • Competing with mechanical dryer<br>• Climate change can effect reliability |
| Indirect solar dryers [19] | • Superior product quality as, the required temperatures can be regulated<br>• Moisture removal rate is high<br>• Retains the color of the food as it is not subjected to ultra violet radiation | • High capital investment<br>• Auxilliary energy source needed for cloudy days<br>• Thermal storage system needed for hours of darkness | • Best for food rich in metal elements like citrus fruits, cucumber, carrot etc | • Low solar energy density compels for a larger collector area |
| Hybrid solar dryer [44] | • Increased efficiency (even on cloudy days)<br>• Can operate for long hours(even at night time)<br>• More controlled and consistent drying environment hence improved drying quality | • Major barrier for small scale industry as initial cost is high<br>• Complex design hence maintenance cost is higher<br>• Require lot of space<br>Operational cost is high | • Can be integrated with smart technology<br>• Can be customised for specific agro products<br>• Easy to scale up | • Reliance on additional resources<br>• Complexities if not managed properly leads to inefficiency of the system |
| Mixed mode active solar dryer[20] | • Better control over drying mechanism hence better drying efficiency<br>• Uses both direct and indirect mechanisms | • Low thermal efficiency | • Can be used to dry any kind of food stuff | • External aids needed to control the drying kinetics and hence increases the capital cost |
| Cabinet dryer | • Compact design makes it suitable for smaller capacity and smaller space<br>• Better temperature control | • Limited capacity | Cabinet dryers with energy efficient system aligning with regulatory requirements will capture the market quickly | • Improper cleaning of the cabinet may lead to contamination of the food products |

**Table 1** (continued)

| Type of Solar Dryer | Strength | Weaknesses | Opportunities | Threats |
|---|---|---|---|---|
| Greenhouse dryer | • Can accommodate more materials<br>• Reduced moisture buildup<br>• Budget friendly | • Temperature and humidity can fluctuate | Green house dryer coupled with PVT, thermal storage etc. can decrease the carbon foot print as well as increase the efficiency | • Mecanical issues can lead to spoilage of food items |
| Tent | • Ecofriendly<br>• Low cost<br>• Versatility | Limited protection | Adaptability for different drying needs | • Open designs can invite pests and dusts<br>• Less durable |

claim better performance of ET collector than the PVTC [45]. Air flux can be made to flow through metallic tubes which can be located beneath the PV panel. This provision enables heat transfer on both the sides of the PV panel facilitating cooling of the PV cells and carrying the heat to the drying chamber [46].

**Compound Parabolic Concentrator (CPC)** Solar absorption can be enhanced by using reflectors or concentrators [48]. Concentrators reflects wide angle of radiation into a small area on absorbers [49]. The beam radiations are reflected on the absorber by several reflectors. Absorbers can have various types of configurations like tubular, flat, wedge etc. A conical concentrator consists of conical reflector generally made of iron or aluminium sheets with mirrors cemented on the surface with insulating material along with some adhesives. The mirror surfaces reflect the radiations directly on the absorber tube. The vertex angle is generally maintained at 90$^{\circ}$C and the solar incident angle at 45$^{\circ}$C [50]. Co- axial conical concentrators display good drying kinetics compared to non-co-axial conical concentrator and parabolic concentrator [51]. Finned photo voltaic panels can be used as absorbers in combination with CPC in solar dryer. This arrangement demonstrates concentrating more radiations and effective use of thermal energy from the panel [52]. The drying time can be reduced by coupling CPC with electric heater before inducting the air into the drying chamber [49].

### Solar Collectors with Tracking Systems

Solar tracking system tunes the surface of the panel or collector in line with the trajectory of the sun. It comprises of single axis and dual axis system. Single-axis systems can move only on a single axis, that is either vertical or horizontal (east or west). The tracker is adjusted manually during the year intermittently. Single axis system is economical, but yields less efficiency [53]. In case of dual axis system, the tracker follows north and south direction too. Though dual axis system is expensive it ensures optimal usage of solar radiation. Active trackers use motors which are connected with two light sensors to evaluate the potency of solar light. Difference in the intensity of the light received by the sensors causes the collector to move to a new position. Signals from the sensors are passed to microcontroller, which operates the motor of the driving mechanism to a new position. Some tracker system also has PV panels installed to power the air blowers and the motors Fig. 17 [54]. The drying period of food stuff can be reduced by installing a tracking system [55]. Almost 50% increase in drying and thermal efficiency is observed with the solar tracking system [56, 57] (Table 2).

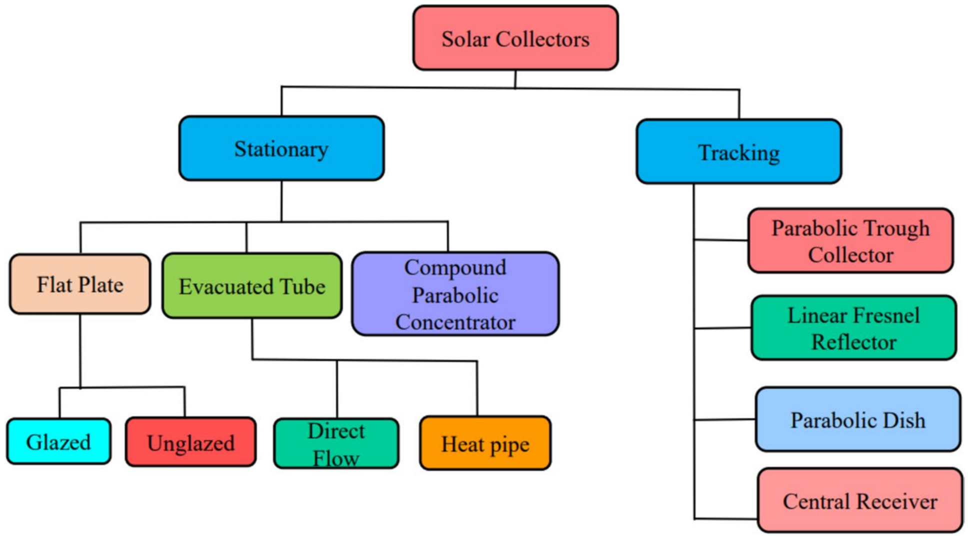



**Fig. 8** Classification of solar collectors [23]

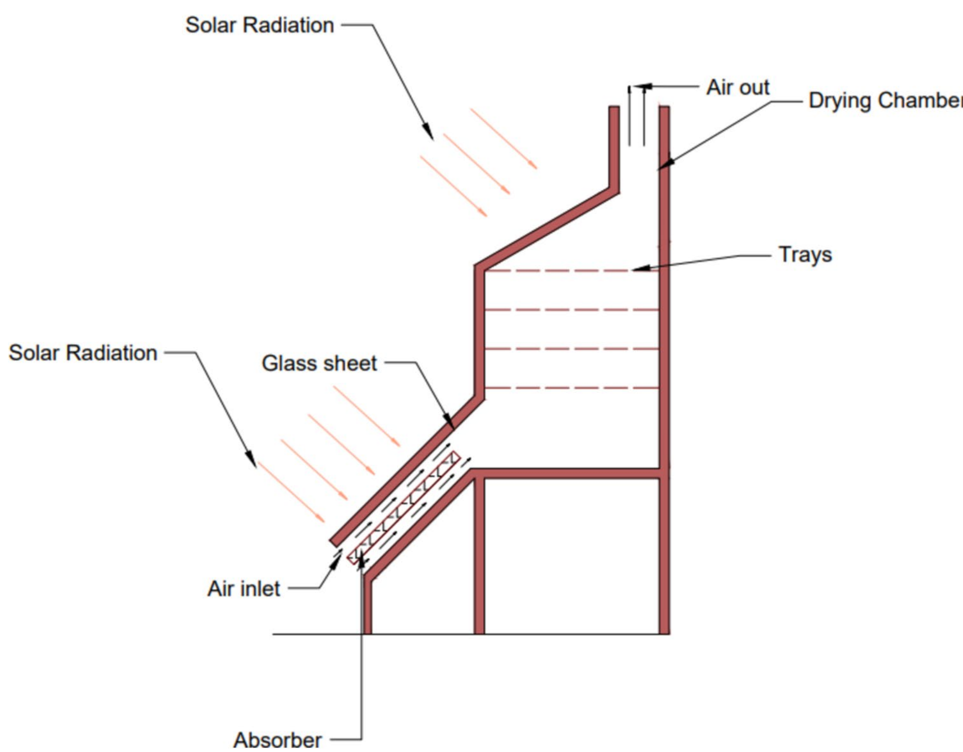



**Fig. 9** MMASD [25]

## Advantages of a Solar Tracking Systems

- Optimal usage of solar radiation than fixed cell
- Economically feasible
- Significant for larger scale projects
- It is automated and does not required supervision once activated
- Can be placed anywhere as a result of tracking system.

## Disadvantages of Solar Tracking Systems

- Cost is higher than fixed collectors
- Dual axis systems are more optimized

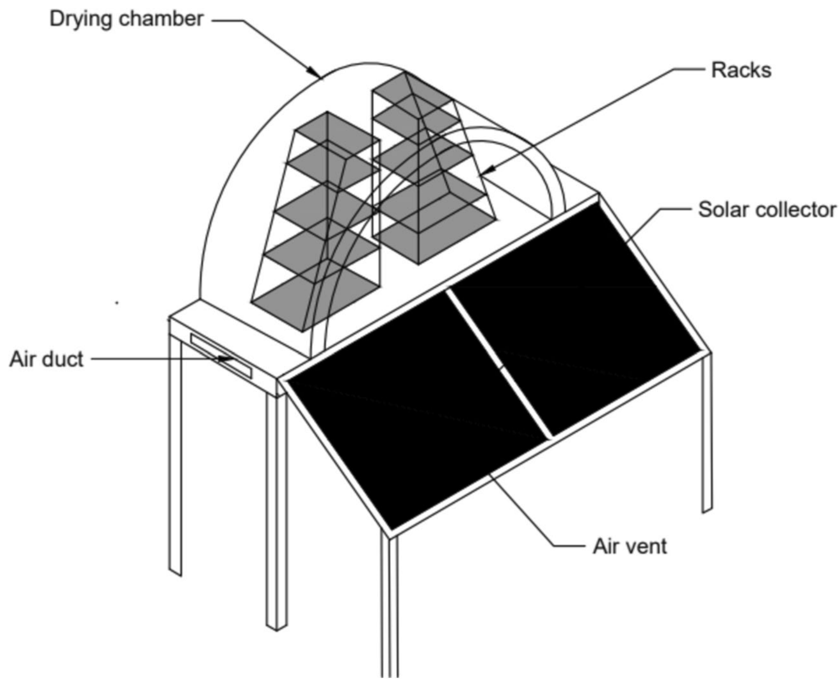



**Fig. 10** Tent type MMASD [24]

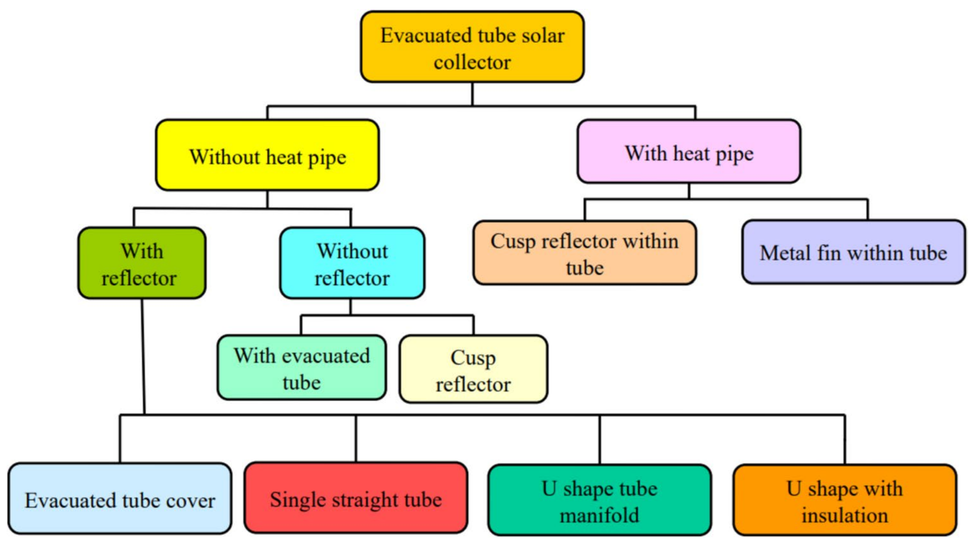



**Fig. 11** Classification of evacuated solar tube collectors [31, 34]

## Absorber

Solar absorbers are different from solar cells. Solar absorbers are located beneath the transparent collector to collect the heat passing through the collector cover and solar cells convert heat into electricity. Absorbers plates are made of stainless steel, galvanized iron, zinc, copper or aluminium. Aluminium absorber plate can be used with copper flow passages to avoid any type of corrosion. Metal absorber cannot fully absorb the incident radiation, so a selective coating of dull black colour is applied on the metallic surface for better absorption. Efficiency of the absorber coating depends on these selective coatings. Selective coatings increase the operation temperature of the system. High absorptivity of beam radiation and low emittance are desirable properties of a selective surface [58]. A wire mesh plate above the main absorber plate in the collector increases the absorption of solar radiation [59]. This offers flexibility in adjusting the thermal characteristics of the solar dryer. Tubular absorber offers more surface area for absorption of incident solar radiation. Tubular absorber yields greater output temperature, power and efficiency [60, 61]. To increase the thermal effectiveness of the solar radiation, Aluminium wool or copper wool can be used along with the tubular absorber or flat plat absorber [3, 62]. Recyclable aluminium cans, can also be used for making tubular absorber [63]. Figure 18 depicts that

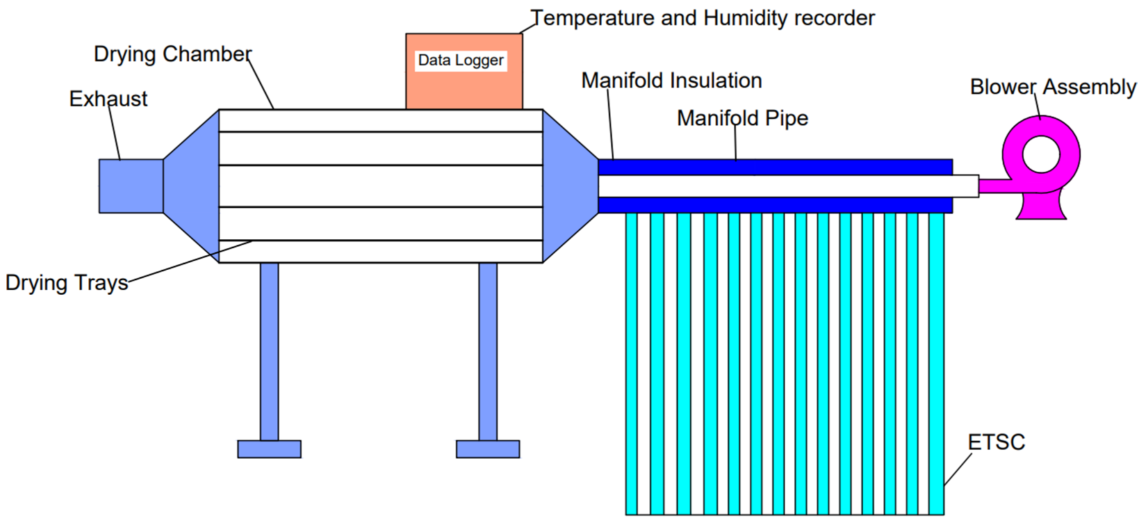
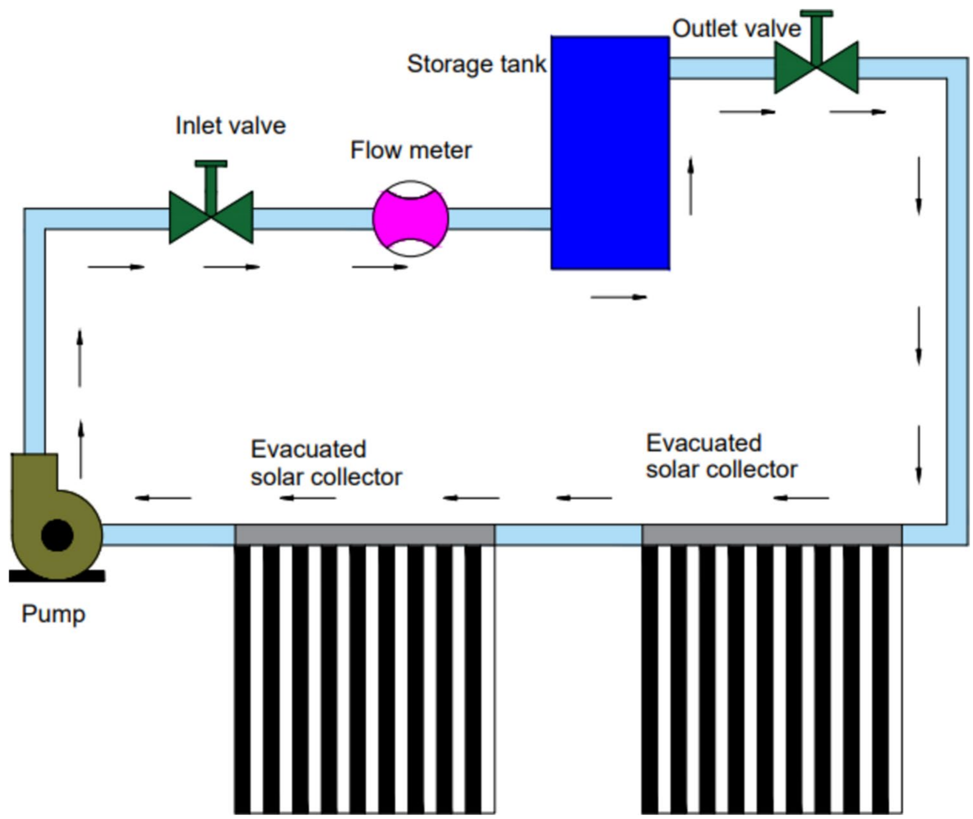



**Fig. 12** Schematic diagram of HP-ETSC [35]

**Fig. 13** Schematic diagram of parallel-type ETSC [42]




using iron mesh inside the tubular absorber can contribute towards waste management and sustainability, yielding clean energy to the society [64]. Corrugated absorbers, generally made of aluminium, provides a large surface area for the absorption [65]. However, the increment in air temperature at the outlet of the absorber significantly depends on its flow rate [66]. Corrugated V shaped absorber made of copper was tested by [67].

Double layered wire net fine meshes can be used as absorber material with V or U corrugations as shown in Fig. 18. These Absorbers can be treated as porous material [69]. Figure 19 demonstrates that corrugated stainless steel wire mesh with different pore size can enhance the heat transfer by enhancing the $h_c$ [70]. Figure 20 shows that the C shaped perforated fin absorbers, have yielded higher Reynolds number. Friction factor and Nusselt number

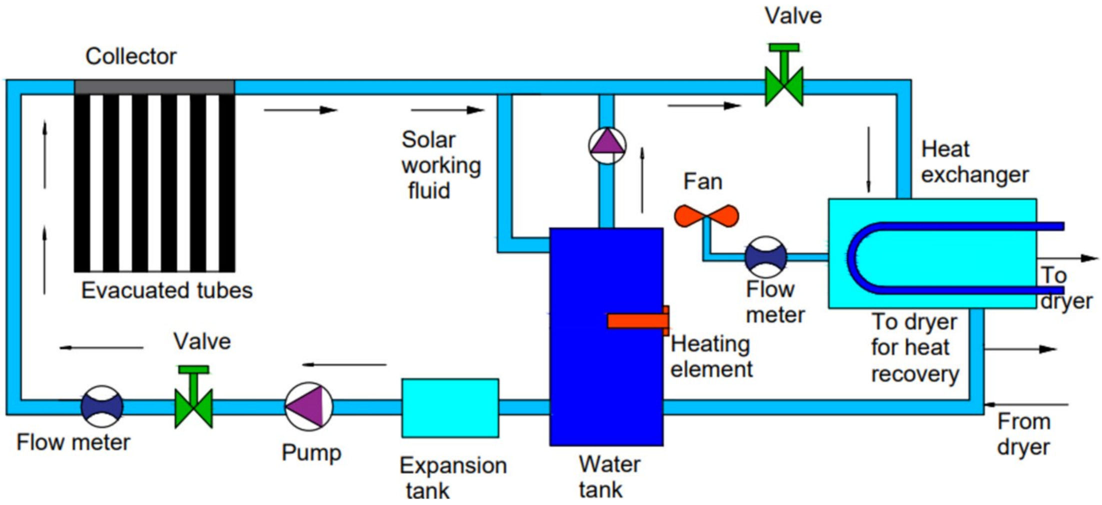



Fig. 14 HP-ETSC with heat recovery system [43]

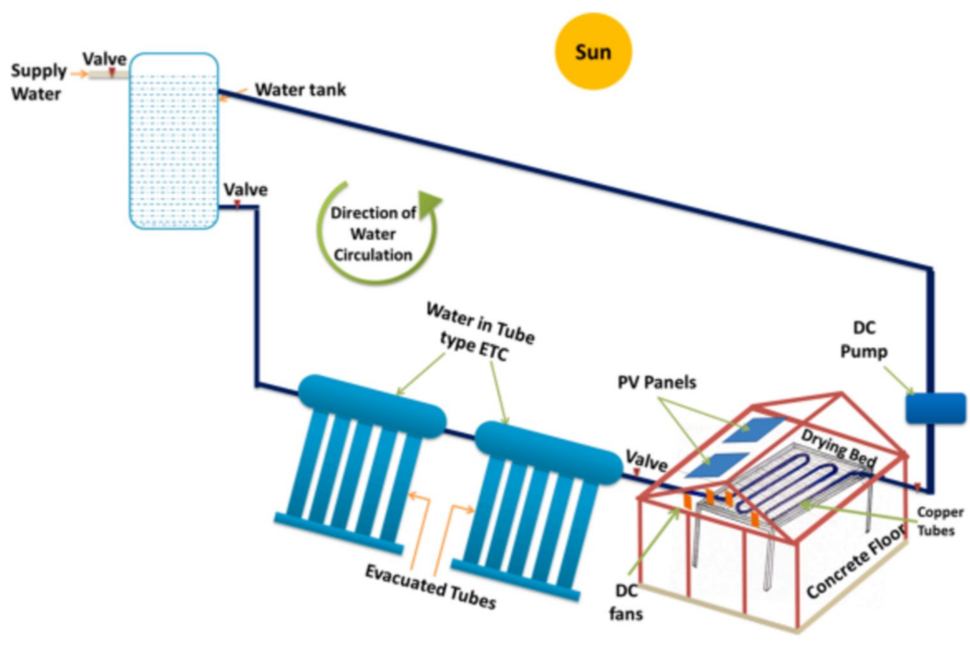



Fig. 15 HAGSD with evacuated tube collector [44]

significantly depends on the Reynolds number. Higher the Reynolds number, higher will be the friction and thus higher will be the convective heat transfer coefficient [71].

Figure 21 a and b, demonstrates increasing roughness of the absorber plate by arc ribs, V ribs, double arc ribs [72–74] to promote the turbulence. The secondary flow through the gap facilitates in intermixing with main flow. Placing discrete staggered ribs increases the Thermo-hydraulic performance parameter like Heat transfer coefficient, heat transfer coefficient, overall heat transfer coefficient, effectiveness and dimensionless numbers [75–79] which is shown in Fig. 22 a & b.

## Reflectors

Reflectors convert solar radiations into useful energy Fig. 23. External reflectors like mirrors can be installed to capture maximum radiation of sun [80]. Solar dryers with north wall reflectors assist in capturing solar radiation particularly in winter at higher altitude [81]. Collectors with North- south Aluminium oxide reflectors with V alignment trough results in higher collector efficiency [82]. Reflectors can be of metals like stainless steel (SS304) and aluminium (Al304) [83]. Reflective spray paints can also be used as reflectors [84]. Attaching reflector improves the collector efficiency and

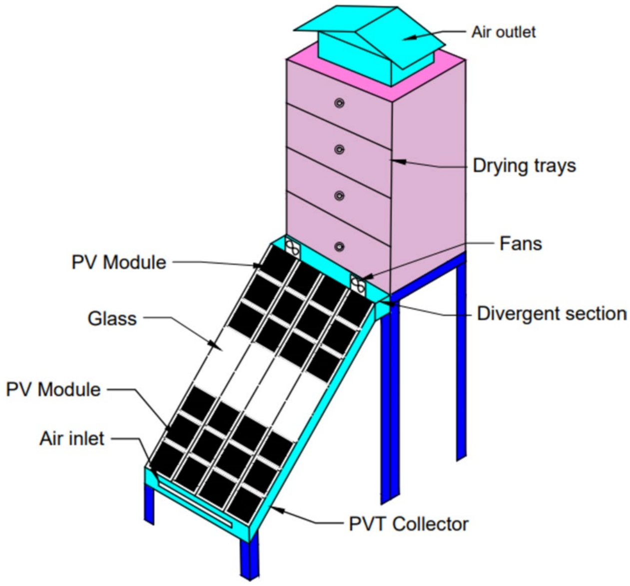



**Fig. 16** PVT Solar dryer [47]

reduces the drying rate significantly. The summary of which is given in Table No. 3 Table 3.

## Drying Chamber

Drying chambers are of two types, direct type and indirect type. Direct type chamber are either made of dome shape or tunnel shape and is covered with glazed plastic cover or glass. The assembly is simple and cost effective. One of the types of direct type chamber is the greenhouse effect. The walls and roof are made of polycarbonate sheets or plastic sheets. Green house dryers are simple in construction and acts as a solar collector too apart from greenhouse effect. Plastic sheets are fixed to steel structure and sealed to prevent rainwater inside the chamber. Fans are installed at proper locations to ensure even distribution of air. Greenhouse chambers can have dome shaped or roof structures. The fluctuations in the temperature, effects the collector efficiency. Installing a chimney above the drying chamber, creates a natural draft of air and thereby ensures

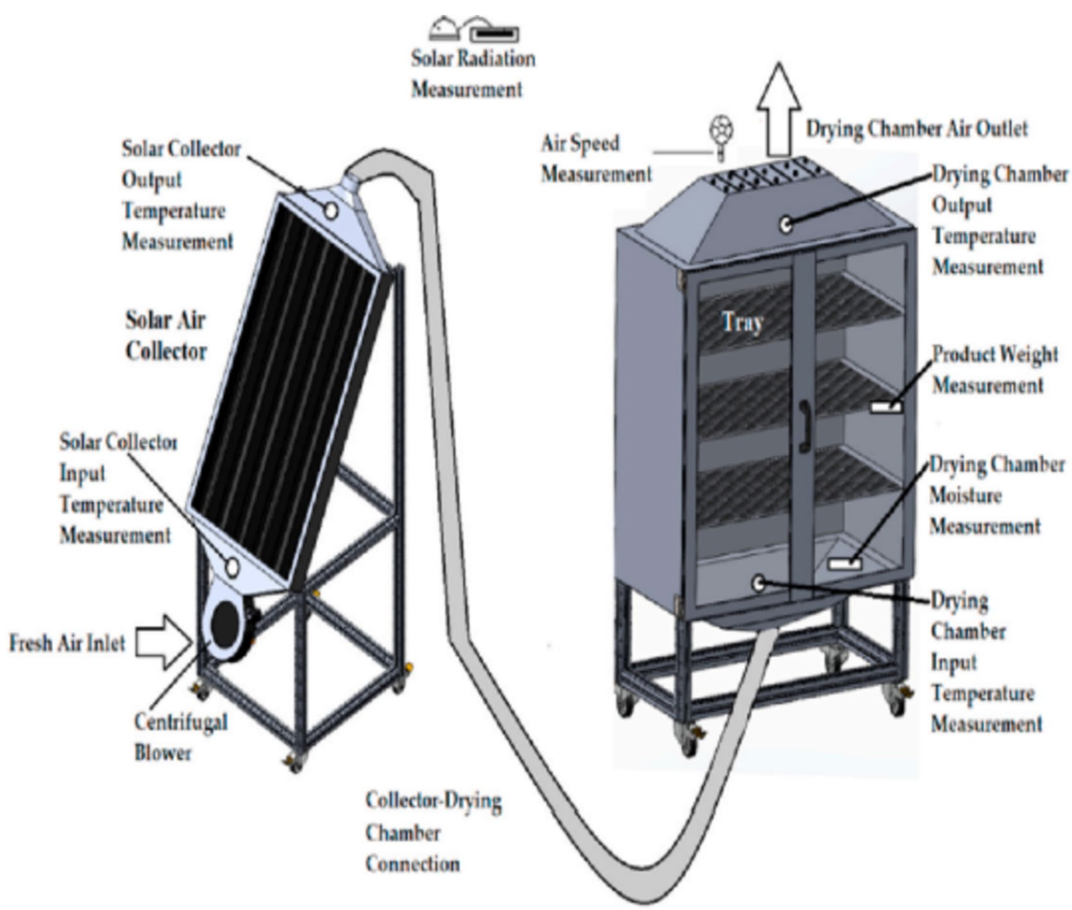



**Fig. 17** PLC solar tracking system [57]

**Table 2** Design and fabrication summary of different solar dryers

| Reference No | Authors | Type of solar dryer | Collector type | Dimensions | Material | Tilt angle | Insulation | Venting of moisture | Glass cover | Reflectors | Absorber material |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [22] | Lakshmi et al. 2019 | Mixed mode forced convection | Double pass flat plate counter flow solar air heater (DPC-SAH) | 2 m × 0.85 m × 0.45 m with 6 trays of 0.58 m (W) × 0. 83 m (L) | Mild steel sheet | — | Wood | On hole at exit | — | — | — |
| [23] | Hegde et al.,2015 | Indirect type | Flat Plate | 1.6 m × 0.6 m | G.I Sheet | $13^{\circ}$ due south | Plywood | | — | — | — |
| [24] | Arun et al.,2019 | Multi-tray mixed-mode solar cabinet dryer (MMSCD) | The flat-plate collector with double-pass airflow passages | The width, height, and volume of the dryer are 0.5 m, 1 m, and 0.25 $m^3$, Each tray area of 0.2 $m^2$ | S304 stainless steel | — | Glass wool of 0.05 m | — | — | — | Copper |
| [26] | Murugavelh et al., 2019 | mixed mode solar tunnel dryer, Forced convection | Flat plate | 2.04 m X1.06 m 0.07 m, 1.12 $m^3$ Tray 0.78mx0.8 m | Stainless steel | — | EPE foam sheet (black color) | — | 8 mm | — | Aluminum sheet |
| [27] | Mehta et al., 2018 | mixed mode tent-type solar dryer | Flat plate | 1.18 m × 2.47 m with collector area of 2.9 $m^2$,Lower rack: 0.44 m × 0.88 m,upper rack:0.33 m × 0.88 m | — | $20^{\circ}$ to horizontal facing south | 0.025 m thick Solid polyvinyl chloride insulation sheet at the bottom as well as side of the collector | 1.2 m × 0.0621 m at the bottom of the collector | 0.004 mm,transmittance > 0.7 for wavelengths 0.2–2.0 µm, opaque to wavelengths > 4.5 µm. T | — | Black aluminium coated polyvinyl chloride sheet of thickness 0.1 mm |

**Table 2** (continued)

| Reference No | Authors | Type of solar dryer | Collector type | Dimensions | Material | Tilt angle | Insulation | Venting of moisture | Glass cover | Reflectors | Absorber material |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [29] | Wang et al., 2018 | Indirect forced convection solar dryer | Evacuated tube | ϕ58 × 1800 mm, Surface area 5.24 $m^2$ | — | $30^{\circ}$ to horizontal facing south | — | — | — | — | — |
| [35] | Malakar et al., 2021 | Forced convection indirect solar dryer(with heat pipe) | Evacuated tube | 15 tubes, Inner diameter = 47 Outer diameter: = 58 mm Length of the tube 1.8 m Copper Heat pipe diameter 0.8 cm, 5 t rays with 1.3 × 0.5 m each, Solar collector area 1.66 $m^2$ | — | $52.35^{\circ}$ | Glass wool | — | — | — | — |
| [36] | Iranmanesh et al.,2020 | solar cabinet dryer equipped with evacuated tube solar collector and thermal storage system | Evacuate heat pipe | Model: SK-H15-45, Inner diameter: 45 mm, Outer diameter: 58 mm, Length of tubes: 1800 mm, Number of tubes: 15, Solar effective area: 1.9 $m^2$, Perforated polyethylene trays 900 mm×500 mm each | — | $35^{\circ}$ | — | — | — | — | Copper |
| [43] | Daghigh et al., 2016 | Solar dryer with heat recovery system | Evacuate heat pipe | Model: DL-PM15-58/1.8, Outer diameter: 58 mm, Length of tubes: 1800 mm, Number of tubes: 18, Solar effective area: 2.06 $m^2$, | — | — | — | — | — | — | — |

**Table 2** (continued)

| Reference No | Authors | Type of solar dryer | Collector type | Dimensions | Material | Tilt angle | Insulation | Venting of moisture | Glass cover | Reflectors | Absorber material |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [44] | Singh et al., 2021 | Hybrid active greenhouse solar dryer | water-in-tube-type ETC | Outer diameter: 58 mm, Length of tubes: 1800 mm Dimension of Heat exchange inside dryer: 2 m×2 m X0.8 m 30 copper tubes of length 1.5 m and diameter 8 mm are placed below the wire mesh fitted in the heat exchanger bed | – | – | – | – | – | – | – |
| [45] | Daghigh et al., 2020 | Active indirect cabin type solar dryer | Evacuated tube | Inner diameter: 47 mm, Outer diameter: 58 mm, Length of tubes: 60 cm | – | – | – | – | – | – | – |

uniform temperature range [88]. Collector efficiency largely depends on the air flow rate. Increased airflow rate ensures higher collector efficiency.

## Selection Criteria for a Suitable Solar Dryer

The need for longer shelf life of food items has revolutionised the drying mechanism systems. Constant effort is exercised to diminish the cost of dried food items, by adopting renewable technology for drying. Since diverse food items contain various proportions of moisture content and hence the drying time varies accordingly, it becomes a herculean task to choose an appropriate solar dryer which can support effective drying mechanism. Each solar dryer has its own merits and demerits of drying mechanisms. The moisture removal mechanism of each dryer depends upon the methods of heat input mechanism. Table 4 demonstrates the parameters for the selection of a dryer.

## Environmental, Economic, and Social Aspects of Solar Dryer

It imperative to consider the lifecycle impact, the choice of materials, land use, and potential effects on local ecosystems of solar dryers to ensure they contribute positively to environmental sustainability. Solar dryers should perform with maximum exergy. Sustainability does not really mean using only sustainable resources. An inefficient solar dryer will produce less available energy and more of waste energy [97]. Energy which is not in mutual equilibrium with the environment has the potential to damage the environment. For any system engaged in energy transaction it is imperative to identify losses. Identification of losses will help in designing an efficient energy system, reducing the ecological damage and there by intensifying sustainability. The sustainability of solar dryer depends on the using the system such that the exergy losses are minimum to the atmosphere. For evaluating optimum efficiency with better accuracy, exergy analysis can be used to identify losses.

Assessment of solar dryer should not be limited to efficiency alone. Sustainability of the designs should also be assessed. For drying processes exergy tool can be applied to sustainable energy applications. Irrespective of the environmental conditions, exegetic-sustainability indices justify the design of the energy system designed [96]. This enables comparison of systems irrespective of their design and weather condition. Exegetic sustainability will help in identifying solar dryers having more energy losses and hence will facilitate in choosing the best solar dryer.

**Fig. 18** Design of V corrugated absorber [68]

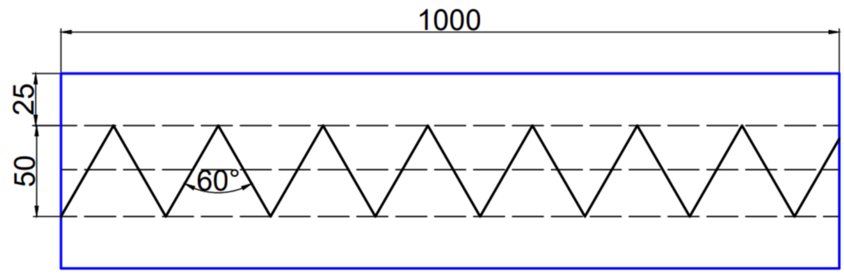



**Fig. 19** Size of different SUS 304 wire mesh [70]

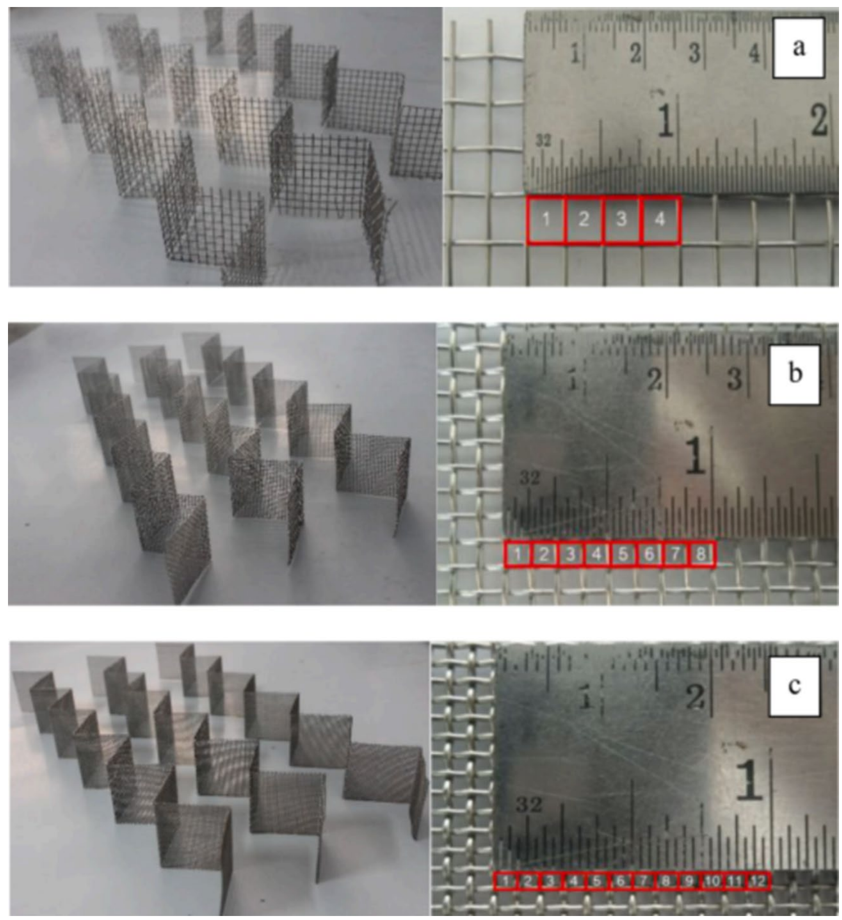
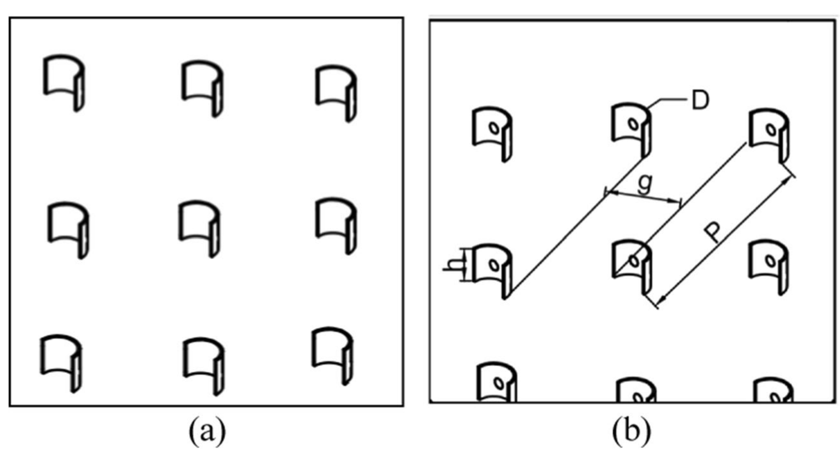



**Fig. 20** Arc shaped **a** non perforated and **b** perforated fins on absorber plate [71]



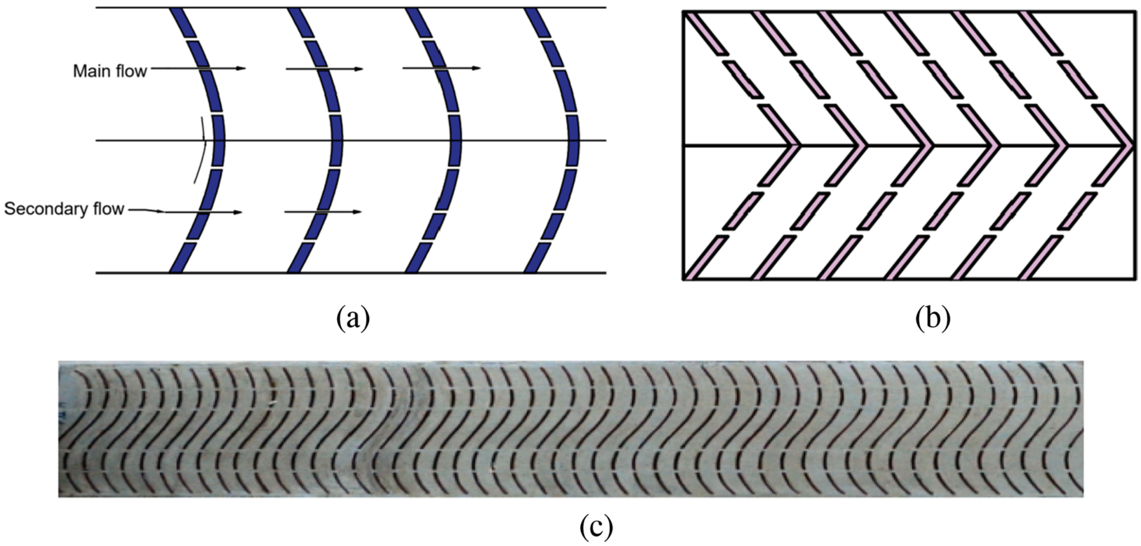



**Fig. 21** **a** Arc rib absorber with symmetrical gaps [72]. **b** V rib absorber with symmetrical gaps [74]

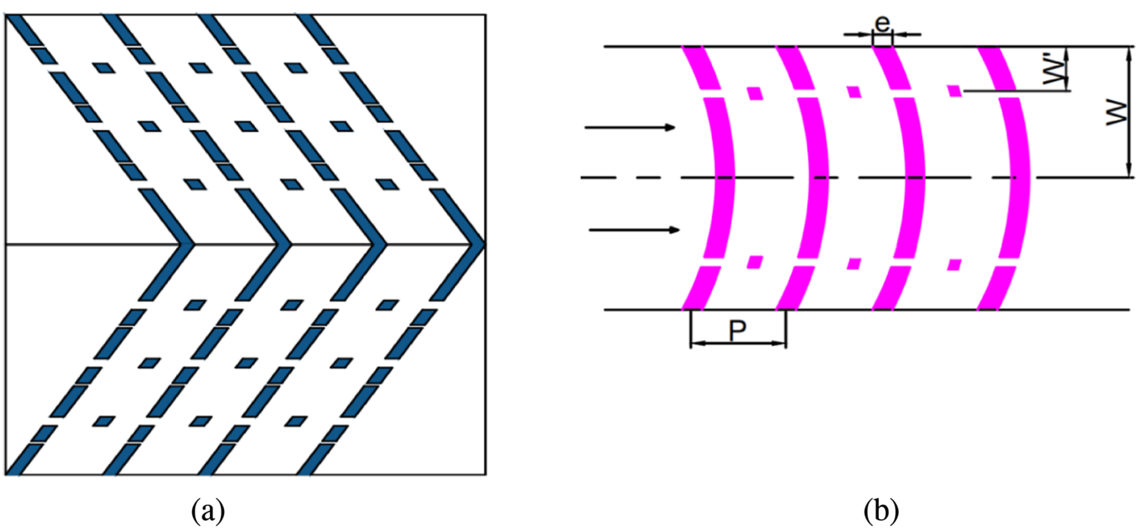



**Fig. 22** **a** V rib absorber with staggered element [75]. **b** Broken arc and staggered rib [79]. **c**: Discrete double arc roughness with symmetrical gaps [73]

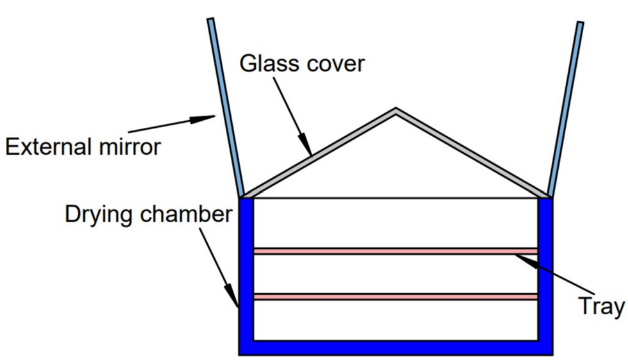



**Fig. 23** Direct type passive solar dryer with external reflectors [80]

While designing any system the effort is to mitigate the energy back to the atmosphere in comparison to the output from the energy system. Quantifying this mitigated energy in terms of money is called carbon credit [90]. The evaluated carbon credit gauges the cost of the amount of $CO_2$ diminished by using solar dryers and lesser the indicator less damage caused to the ecological environment [98]. Solar dryers functioning in active mode emit more $CO_2$ emissions [99]. The increased emissions are attributed to auxiliaries installed like exhaust fan, battery and collectors involved in the assembling the solar dryer.

The economic evaluation of dryers with different technologies helps in comparing it with the conventional one

**Table 3** Summary of impact of reflectors on performance parameters of solar dryer

| Authors | Items dried | Reflector material | Thickness in mm | Impact of attaching Reflector to solar dryer |
|---|---|---|---|---|
| Dharmapuri et al., 2022 [80] | Grapes | Glass mirrors | —- | Reduction in drying time by 37.5% and increase in the temperature by 20% |
| Maiti et al., 2011 [82] | Papad | anodized aluminium sheets | 0.5 | Collector efficiency improved by 46.25% |
| Teklu H et al., 2020[87] | Tomato slices | Glass film sticker with 88% reflectivity | 0.05 | Temperature increased by 57.14%<br>Drying rate increased by 8% for 10 kg<br>And 14% for 5 kg load |
| Rashidi et al., 2021[86] | Oleaster | Steel sheets | — | Reduction in drying time by 25% |
| Kabeel AE et al., 2022 [85] | Anchovy fish | Glass mirror | –- | Reduction in drying time by 22.25% and increase in drying rate by 66.66% |
| Spall et al.,2020 [81] | Carrot slices | Aluminised reflector with 90% reflective | 0.8 | Reduction in drying time by 20.00% |

**Table 4** Criteria for the selection of suitable solar dryer [89]

| Criteria | Characteristics | References |
|---|---|---|
| Physical attributes of a dryer | Space requirements | [90] |
| Thermal performance | Input airflow rate<br>Solar insolation<br>Drying time<br>Drying temperature (depends upon the food to be dried)<br>Relative humidity | [91] |
| Characteristics of food material | Initial and final moisture content<br>Related temperature required<br>Drying time | [92] |
| Quantity to be treated | Quantity to be handled in a day/hour<br>Preprocessing<br>Batch production<br>Continuous production<br>Shrinkage | [93] |
| Quality of the product | Taste<br>Colour<br>Final moisture content<br>Contamination<br>Food density<br>Soiled food<br>Burned food<br>Overdryed food | [94] |
| Facilities at the site | Space<br>Solar insolation | [95] |
| Commercials | Cost<br>Benefit<br>Payback time | [96] |

[100]. The overall cost of the dryer is calculated by considering the costs such as design, construction, installation, logistics, annual operating cost and any kind of maintenance and labour involved. If any auxiliary device is operating on electricity, then it should be added in the operating cost [101]. Another financial parameter like NPV is used to assess the potentiality of investment. Higher NPV indicates less financial loss. IRR facilitates in assessing returns on investment. Higher the IRR higher will be NPV even in case of increment in interest or inflation [102].

## Challenges and Future Prospects

Challenges for implementation of solar dryer can be attributed to technical, economic and societal barriers.

### Technical Barriers

Some technologies or systems are inherently complex and require specialized knowledge or skills. This complexity can be a barrier to widespread adoption or effective utilization. Integrating solar dryers with existing agricultural or food processing systems can be challenging [103]. Ensuring that the dryer fits well with current practices and infrastructure requires careful planning. Automation and Control: Incorporating automated controls and monitoring systems to optimize the drying process can be technically challenging and expensive. Issues such as software bugs, hardware failures, or system downtime can prevent the effective use of technology. Ensuring that systems are secure from cyber threats is a significant challenge and a barrier to the adoption of new technologies. There are material and construction challenges where durability of the material is a major concern. The material used in construction must withstand harsh and variable environmental conditions. Optimising cost and durability of material is a herculean task. Designing a solar dryer that effectively captures and utilizes solar energy can be challenging. The design must consider factors like air flow, temperature control, and material to ensure efficiency. For regions with varying weather conditions, it is difficult to maintain consistent temperatures within the dryer. Inconsistent temperatures can affect the drying process and the quality of the dried product. Scaling up dryers to handle larger quantities of products can be technically challenging. Ensuring that the dryer remains effective and efficient at larger scales requires careful engineering.

Solar dryers require regular maintenance to ensure they function properly. This includes cleaning, checking for wear and tear, and addressing any issues that arise. Ensuring that users have the skills and resources to perform maintenance can be a barrier. Effective operation of solar dryers often requires training. Users need to understand how to operate the system, monitor its performance, and troubleshoot problems. Continuous research will lead to improvement in technology, enhance efficiency, and reduce costs. Limited access to advanced technologies or research can slow down the development and adoption of solar dryers. Solar dryer technologies may need to be adapted to different climates and applications, which can involve significant technical adjustments and innovations. Measuring and monitoring the efficiency & product quality, can be technically demanding. Reliable sensors and data analysis tools are necessary for effective monitoring. Addressing these technical barriers requires a multidisciplinary approach, involving engineering, materials science, and user training to ensure that solar dryers are both effective and practical in various contexts.

### Economic Barriers

High costs associated with developing, implementing, or maintaining technology can be a significant barrier [104]. This includes not just the initial investment but also ongoing operational costs. Limited access to capital or investment can impede the ability to innovate or scale technological solutions. Disparities in wealth can result in unequal access to technology [105]. Those with fewer resources may not benefit from technological advancements. Low demand in certain economic conditions can make it less feasible for companies to invest in or adopt new technologies. Compliance with regulations and standards can be costly and complex, potentially stifling innovation**.**

### Societal Barriers

Individuals or organizations may resist adopting new technologies due to comfort with the status quo or skepticism about the benefits [106]. Lack of education or training can prevent people from effectively using or benefiting from new technologies. Societal norms and values can influence the acceptance and use of technology. For example, privacy concerns or ethical considerations may impact how certain technologies are adopted. Societal barriers such as inequality or lack of access to resources can prevent certain groups from benefiting from technological advancements. Government policies and regulations can either enable or obstruct technological progress, depending on how they are designed and implemented.

## Conclusion

Designing of solar dryer should concentrate on capturing maximum solar radiation. It should be cost effective. The design should not be limited to only rural applications. Focusing on processors and consumer's need during research, will leverage commercialisation of the product which should benefit rural as well urban applications. The dryer should be feathery and durable and material selection for the dryer should be such that it can with stand harsh weather conditions. Effective airflow management and the temperature regulation inside the solar dryer will prevent over drying of food. Parameters like capacity, area, cost requirement and environmental consideration should be considered while selecting a collector. It should function in all seasons with variety of food products, for maximum payback. Incorporating automation system will enhance the efficiency of the system, especially in shady days. The nutrition value, colour and taste of dried food should be checked with different technologies, as the revenue generation will significantly depend upon the quality of the product. Overall market penetration will be more with distributed production than centralised production, thereby reducing the logistic costs and storage problem.

**Authors Contribution** Jayashri N Nair: Concept, Methodology, Writing original draft, Reviewing and editing Dhana Raju: Review and Editing T Nagadurga: Review and Editing.

**Data Availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing Interest** The authors declare no competing interests.

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